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Iowa State University of Science and Technology
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RELATIONSHIP OF FACTORS CONTRIBUTING TO GULLY DEVELOPMENT
IN LOESS SOILS OF WESTERN IOWA

by

Craig Eugene Beer

A Dissertation Submitted to the
Graduate Faculty in Partial Fulfillment of
The Requirements for the Degree of
DOCTOR OF PHILOSOPHY

Major Subjects: Agricultural Engineering
Civil Engineering

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Dean of Graduate College

Iowa State University
Of Science and Technology
Ames, Iowa

1962

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INTRODUCTION

Gullying became a serious problem in America soon after the beginning of modern agriculture. In 1939, Bennett (5) stated that surveys showed that there were more than 200 million active gullies in the United States. Since 1939 more gullies have developed. However, much progress has been made in the control of gullies through the efforts of United States governmental agencies working with individual farmers or with organized watersheds.

In Iowa many gullies are controlled on a watershed basis by the activities of the Soil Conservation Service working through the auspices of Public Law 566 and the Little Sioux Flood Prevention Program. The magnitude of the gully problem is indicated by the value of the expected land damage for the next 50 years. The following values in Table 1 are taken from cost-benefit ratio calculations for selected watershed work plans in Iowa.

Table 1. Estimated average annual damages from gullying in Iowa watersheds

Watershed	Size (mi ²)	Average annual gully damage
Badger Creek	53.67	\$33,523
Crooked Creek	35.4	5,937
Big Park	11.99	25,608
Simpson Creek	3.7	3,535
Pony Creek	30.2	23,192
Indian Creek	15.3	15,265
Davids Creek	61.4	41,503
Ryan - Henschal	14.7	14,345
Average = \$719/mi ²		

The sample in Table 1 shows an average expected gully damage of \$719.00 per square mile per year. Presently there are 1,016 square miles of organized watersheds whose directors have applied to the State Committee for assistance under Public Law 566. There are 2,678 square miles eligible under the Little Sioux Flood Prevention Act. Since all but 200 square miles of these watersheds are located in the western one-third of Iowa where the gully problem is most serious, it is evident that if the average damage figure from Table 1 were applied, the annual gully damage in Iowa is sizeable.

Under present practices, the feasibility of gully control is based on an economic evaluation of the dollar value of the estimated land destruction in the next 50 years. It is necessary, therefore, to predict with the greatest possible accuracy what the future gully development will be.

OBJECTIVES

There are two possible approaches to the solution of the problem of predicting the rate of gully advancement.

1. To evaluate the basic forces relating to soil detachment and movement as a function of hydrologic, geologic and hydraulic variables.
2. To use the history of the previous rate of development as a basis for predicting the future rate of development.

The basic approach listed in Item 1 is preferable. However, gully-ing is a complex phenomena which involves many variables, and more research on individual components of the process is needed before any attempt is made to integrate all basic components of the gullying process.

All methods currently used to predict the rate of gully advancement involve the approach listed in Item 2. The gully history, determined with varying degrees of accuracy, is then projected to estimate the future gully advancement.

It is the general objective of this study to use the approach in Item 2 with the following specific objectives.

1. To select gullies with varying watershed sizes and determine, as accurately as the method permits, the amount of gully growth for a given period by the use of land surveys and the use of aerial photography which has ground control.
2. To relate the gully growth in the given period to hydrologic, gully geometry and watershed variables.

3. To define relationships between factors which are associated with the geometry of the gully.

REVIEW OF LITERATURE

The published and unpublished works on gully development or related subjects usually can be classified under the headings of qualitative discussions of the factors involved, empirical relationships based on past history, interviews and human judgement or hydraulic and geometric relationships for ephemeral stream development. Each of the categories will be discussed separately in the following paragraphs.

Qualitative Factors Related to Gully Development

A very detailed account of observations of the factors causing gully development is given by Ireland (9) in a study conducted in the Piedmont area of South Carolina. In this study four distinct stages in gully development are described. These stages are described qualitatively; however, they are pertinent to the soil types of the Piedmont in which there are three distinct horizons. The first stage is the formation of channelized flow. This channelized flow arises from a natural irregularity in the soil surface or can be initiated artificially by tillage or earthwork operations performed by man. As described in the Piedmont study the first stage consists of the development of the channel through the top soil and into the upper part of the B horizon. The second stage is identified with the formation of overfalls or gully heads which progressively move up the gully with the subsequent deepening and widening of the gully. Stages three and four are the periods of readjustment or healing and final natural stabilization of the gully.

In the Piedmont study, Ireland (9) cites four major causes for the

upstream movement of the overfall. They are lip scour, plunge pool cutting, caving and seepage, all of which may act individually or collectively. Water flowing into the deepened gullies from higher channels plunges to the floor as waterfalls or in rare cases cascades down the walls. Waterfalls formed in this way tend to carve nicks in the gully walls and depressions in the gully floor which together are described as plunge pools. In this soil type, which has a highly erodible C horizon, the action of the water overfall creates a cave or depression underneath the B horizon. This gives a projecting or overhang effect to the B horizon. With further saturation the strength of the B horizon is reduced with the resulting formation of cracks and the ultimate breaking off of the overhanging projection of the B horizon. Since the C horizon in this particular soil type becomes highly erodible as soon as it is wetted, considerable weakening was noted in the C horizon from seepage or back trickle. The back trickle results from the surface tension of the water which causes it to cling to the face of the projecting B horizon and to drip backward and down into the caved out portion of the C horizon. In the Piedmont study this back trickle effect had been noted in an actual storm. It is also important because the back trickle can result from a very low flow in the gully.

The width between the gully walls increases as the gully head moves upstream. In the Piedmont study, Ireland (9) cites three methods of the widening of the gully, all of which produce cracks parallel to the gully with the ultimate slumping in of the bank material. When gully erosion cuts a deep trench into the soil, the equilibrium of the neighboring soil

is disturbed. Lateral pressures are no longer equal and there is a tendency for the soil to move slightly toward the side of reduced pressure. If the gully walls are steeper than the normal angle of repose for the material, they tend to cave off to the flatter slope. The tension produced in this way is expressed in the field as vertical or steeply dipping cracks which are essentially parallel to the gully edge and vary in distance from a few inches to many feet from the edge of the gully. After the crack has been formed, widening of the crack with the ultimate slumping may be facilitated by the wetting and drying, heating, cooling and freezing action.

Bank caving may also be caused by the flowage or plastic movement of the rotten rock or parent material in the lower part of the gully walls. This factor again assumes importance only when dealing with a particular C horizon and may become critical when the C horizon is saturated with water and loaded beyond a critical point. If the bottom of the gully is close to the water table very little surface water may be needed to produce saturation and plastic flow. Methods of lesser importance are the spalling and the action of frost or weather in producing the widening of the gully banks. Spalling is referred to as a falling of relatively thin sheets of soil from the gully walls.

In the Piedmont study, Ireland (9) states that the size and slope of the drainage basin, the land use, the character of soil, and the depth and shape of the gully head were important factors that influenced gully-ing. The study does not attempt to classify the factors according to their relative importance in the rate of gully development. However, it

was noted that seasonal variations were quite distinct, and watershed area alone did not explain the rate of gullying. The slope of the drainage basin was a vital factor in the rate of the gully development. Also the land use, as it affected the rate and quantity of runoff, was considered to be important.

A qualitative discussion of the characteristics of gullies is also given by Lueder (11, p. 50). He makes the following statement.

The characteristics of gullies that have significance to interpretation are those that, in aggregate, describe their topographic expression:

1. Characteristics of dimension (length, width, depth),
2. Characteristics of shape (cross-section, plan, profile),
3. Characteristics of supplement (special features).

When an attempt is made to interpret terrain conditions by analysis of gullies, all these characteristics should be considered.

In the discussion of the dimension characteristics, it is intuitively reasoned that the length, width and depth are a function of the age of the gully, the hydrologic details and the soil characteristics. Therefore, all other factors being equal, it is stated that the length, width and depth should be proportional to the age of the gully. Lueder recognizes, however, that an unbalance in the factors could counteract this tendency.

In analyzing the shape characteristics of gullies, the cross section could be estimated by the use of soil mechanics. The maximum critical height that a gully side would stand without slumping would be computed. This involves the assumption of a plane of failure as well as knowledge of the physical characteristics of the soil. Calculations show that for most soil types the value of the critical height is small. Thus the laterally unsupported material fails by sliding or slumping, and except

in extremely young gullies, the cross section would not have vertical sides. Further, the plan and profile are largely dependent on the type of soil and age of the gully. Lueder (11) suggests that all other things being equal, an old gully in impervious soil would have more tributaries than a young gully in permeable soil. Also a gully in porous, cohesionless soil would have a steeper gradient than one in impervious soil.

A special class of gullies is observed in loessial deposits. These gullies develop "pinnacles" and "buttresses", which are remnantal loessial materials (in situ), at their head ends. Their existence reflects the peculiar characteristics of loessial deposits, and most particularly their high vertical porosity and critical heights.

The following statement from Lueder (11, p. 51) suggests why voluminous amounts have been written on the qualitative aspects of gully development while quantitative aspects have largely been omitted.

It is rather unfortunate that no quantitative observational data, prepared upon a comparative base, have yet been amassed regarding the relationships among length, texture, erodibility, age, and hydrology. It is possible that such data would prove so complex as to defy other than general analysis. Even general analysis would be of value, however.

Empirical Relationships for Predicting Gully Development

Since the applied relationships have been in the category of predicting future rates of gully growth, it is plausible that most of the present techniques involve a past growth factor which is modified to predict a future growth rate. Normally there is no quantitative basis for adjusting the growth factor as is indicated by the following excerpt from the Hamburg Watershed Work Plan (7).

A set of 1938 aerial photos of the areas were studied stereoscopically and the extent of gully erosion at that time plotted on tracing paper overlays. Onto these overlays were then plotted the extent of gully development as shown on the 1955 aerial photos. A measurement of the intervening areas provided a means for determining the past annual rate of gully growth. . . . Based upon field observations conducted in the past, these rates of past gully growth were adjusted to provide estimates of future rates, taking into consideration the extent of land treatment measures that have been installed recently and those planned to be installed; the topography and gully gradients that would be encountered in any future gully advance; the change of soil types; the change in depth of gullies; and the drainage area remaining and susceptible to damage. On this basis, a rate of gully development was established for the future 50-year period.

In the above report, the volume of gully erosion was determined by multiplying the present existing cross-sectional area by the predicted rate of linear advance.

A procedure was suggested by Luebcke (10) for evaluating the percent reduction in gully growth based on a reduction of the volume of runoff. This procedure involved taking a given gully cross section and computing the velocity in the section for varying stages. With the aid of a synthesized hydrograph which was divided into portions representing increments of runoff, it was possible to determine the velocity, V , in the section for a given volume of runoff. Luebcke further used two indexes defined as follows:

1. Detachment index = V^2 multiplied by acre feet of runoff.
2. Debris capacity index = $V^{3.2}$ multiplied by acre feet of runoff.

Thereby with the indicated computations it was possible to arrive at a curve relating inches of runoff to the debris and detachment indexes.

The percent reduction in the indexes, due to the influence of land cover

on runoff, becomes a measure of the change in erosion. However, no attempt was made to compare the procedure with field measurements of gully growth.

The geology staff of the Washington office of the Soil Conservation Service (1) have prepared an equation for predicting the rate of advancement of gullies. The erosion is given by the product of the factors in the following equation.

$$R_e = R \times P \times O \times F \times U \times M \times A \times C \times W$$

Where: R_e = computed future rate of erosion for a given reach.

R = past rate of erosion.

P = precipitation factor.

O = rainfall occurrence or frequency factor.

F = flow duration factor.

U = cover and runoff factor.

M = erodibility factor.

A = drainage area factor.

C = flow concentration factor.

W = ground water factor.

Each of the above factors are determined in the following ways.

$$R = \frac{\text{total length of gully}}{\text{age of gully}}$$

$$P = \frac{\text{long-time annual precipitation}}{\text{gully life average annual precipitation}}$$

O is obtained from a table which was prepared by plotting a

synthetic precipitation frequency curve and comparing the areas under the curve for any period within a 50-year period, with a maximum probable occurrence up to a 100-year frequency.

$$F = \frac{\text{flow duration of reach, e (arbitrarily established)}}{\text{flow duration of present gullied reach}},$$

where the flow duration is determined by subtracting the time of concentration of a given reach from a storm duration greater than the maximum time of concentration for the watershed area.

A storm duration of 1.0 hour is considered the allowable minimum.

U is obtained from a table relating cover and hydrologic soil groups.

M is the relationship between the resistance to erosion of the material through which the gully has already cut and the resistance to erosion of the material through which the gully will cut in the future. It is normally assumed to be unity, for no specific values are given for conditions where the value might not be unity.

$$A = \frac{\text{total drainage area}}{\text{drainage area through which gully has cut}}$$

$$C = \frac{\text{concentration of water over present and past gully head}}{\text{concentration of water over future head}}$$

This factor is a matter of judgement and again usually assumes the value of unity.

W is not evaluated.

A limited amount of work on obtaining a relationship between the gully width, and the depth and cross sectional area has been done by

Heinemann (8) of the Agricultural Research Service. Based on 25 samples this work gives the following relationship:

$$Y = 0.0713X - 19.82 \quad .$$

Where: Y = gully width in feet.

X = cross-sectional area in square feet.

The above relationship incorporates the soil mechanics and geologic aspects of the gully, and such a relationship is valuable in determining the volume of a gully since the width may be accurately determined from aerial photos. In the study, however, there was no correlation between the gully width and gully depth.

Geometric Relationships of Ephemeral Streams

From a study of the Brandywine Creek in Pennsylvania, Wolman (14) indicates that the shape and profile of the channel appear to be related to the interaction of a minimum of seven variables. These variables are discharge, width, depth, velocity, water surface slope, roughness as a measure of frictional resistance and sediment load. At each cross section studied on Brandywine Creek an increase in discharge is associated with the following behavior of the other variables.

1. The width increases slowly or remains relatively constant.
2. Both the depth and velocity increase, the velocity as a rule increasing more rapidly.
3. The roughness decreases.
4. The suspended load increases rapidly.

5. The slope of the water surface remains practically constant.

In Items 1 and 2 above it was found that when each of those variables were plotted against the discharge, Q , on log paper a straight line usually resulted. This showed these variables to be a parabolic function of the discharge. It was found in this study that the exponents of Q in these parabolic equations for width, depth and velocity will sum to 1.

INVESTIGATION

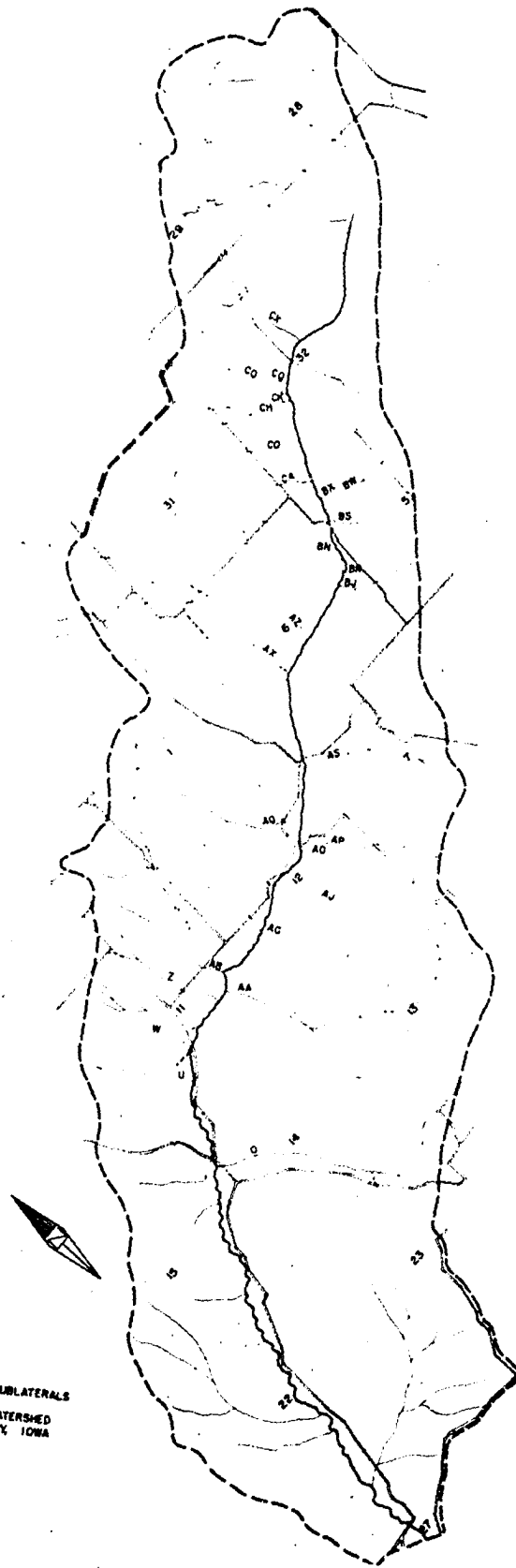
Selection of Gullied Areas

The criteria governing the selection of gullies were as follows.

1. Data must be available to determine accurately the gully development for a 20-year period. It would be highly desirable to divide the 20-year period into two or three intervals which would increase the number of independent samples.
2. The land treatment and watershed cover must be available for the 20-year period.
3. Recording rain gage records should be available from a station located near the gullies to be studied.

The area which was chosen for the gully study was Steer Creek Watershed located in Harrison County, Iowa. Figure 1 shows this watershed contains approximately 14 square miles with the main gully extending upstream for 10 miles. Extending from the main, there are many laterals and sublaterals which are active gullies. Each lateral on which data were obtained is labeled as shown in Figure 1. A typical gully from this watershed which has overfalls developing along the sides is shown in Figure 2. In 1942 the Steer Creek Watershed was surveyed for a structural program to control the gullies. Since the structural program involved the design and construction of earth dams, profiles were obtained on all the active gullies; cross sections were made on most of the gullies, and topographic maps were made at many sites. However, the structural program was never installed on this watershed, and many of the gullies

Figure 1. Map of Steer Creek Watershed located in Harrison County, Iowa



MAIN, LATERALS & SUBLATERALS
OF
STEEN CREEK WATERSHED
HARRISON COUNTY, IOWA

Figure 2. Typical gully with side overfalls and an overfall at the head in Steer Creek Watershed



have developed under the same vegetative cover and land use that existed in 1942. Some of the gullies were filled and reshaped into waterways between 1942 and 1960.

Methods of Obtaining Data

Functional relationships which relate the factors involved in gully development have not been derived from previous research and were not known. Therefore those factors contributing to gully development which have been discussed qualitatively and which could be quantitatively evaluated were set forth and evaluated from aerial photographs, precipitation records, ground surveys, original land surveyor's notes and personal interviews.

Aerial photographs

Aerial flights for 1938, 1949 and 1961 were obtained for Steer Creek Watershed. The 1938 and 1949 flights were secured from the United States Department of Agriculture Commodity Stabilization Service and had a photography scale of approximately 1 inch equal to 1650 feet. The 1961 flight was contracted by the Iowa Agricultural Experiment Station and was flown before leaves appeared on the trees. This flight had a photography scale of approximately 1 inch equal to 1000 feet. Before the flight, targets were placed on the ground at right angles to the flight line and were visible on the photograph. By chaining the distance between the targets, it was possible to determine the exact scale of any photograph along the flight lines.

In all cases where aerial photographs were available, diapositives

of each negative were secured and used in a Kelsh Plotter. Through the cooperation of the State Conservationist and State Engineer of the Soil Conservation Service at Des Moines, Iowa, the services of the Kelsh Plotter of the Cartographic Unit (Soil Conservation Service at Milwaukee, Wisconsin) were made available. The Kelsh Plotter is an instrument which creates a spatial model from stereo-matched diapositives and transmits the spatial model to a topographic map with a four- to five-fold enlargement. From the Kelsh Plotter it was therefore possible to delineate on the topographic map the gully outlines, land treatment measures, land use, subwatershed outlines and the natural drainageways from the gully overfalls to the subwatershed divides. Figure 3 shows the information which was traced on the topographic map by the Kelsh Plotter. The watershed of lateral gully AB from the 1961 flight is included in the figure. Since the 1938 and 1949 photography were on the same scale, the information was superimposed on one map as shown in Figure 4.

Ground surveys

The ground survey which was made by Soil Conservation Service personnel in 1942 provided means for determining the gully outlines, gully cross sections, gully profiles and land use for that year. This information was also made available through the cooperation of the Soil Conservation Service at Des Moines, Iowa. The scale of the 1942 topographic maps was 1 inch equals 200 feet which was the same as the map plotted by the Kelsh Plotter for the 1961 flight. Thus it was possible to obtain the 1942 and 1961 data from the same scale. The 1938 and 1949

Figure 3. Map of lateral AB obtained by a Kelsh Plotter from 1961
flight

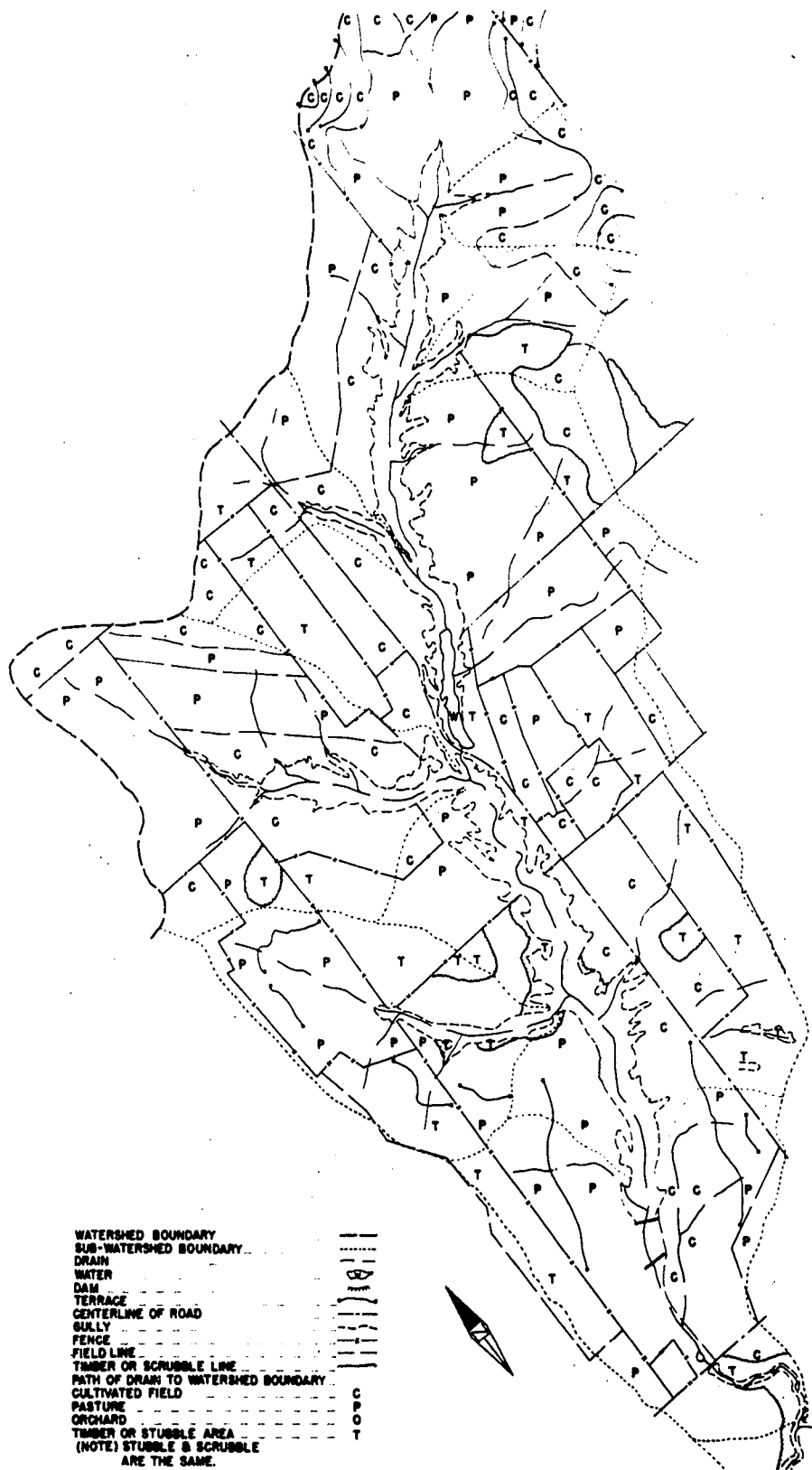
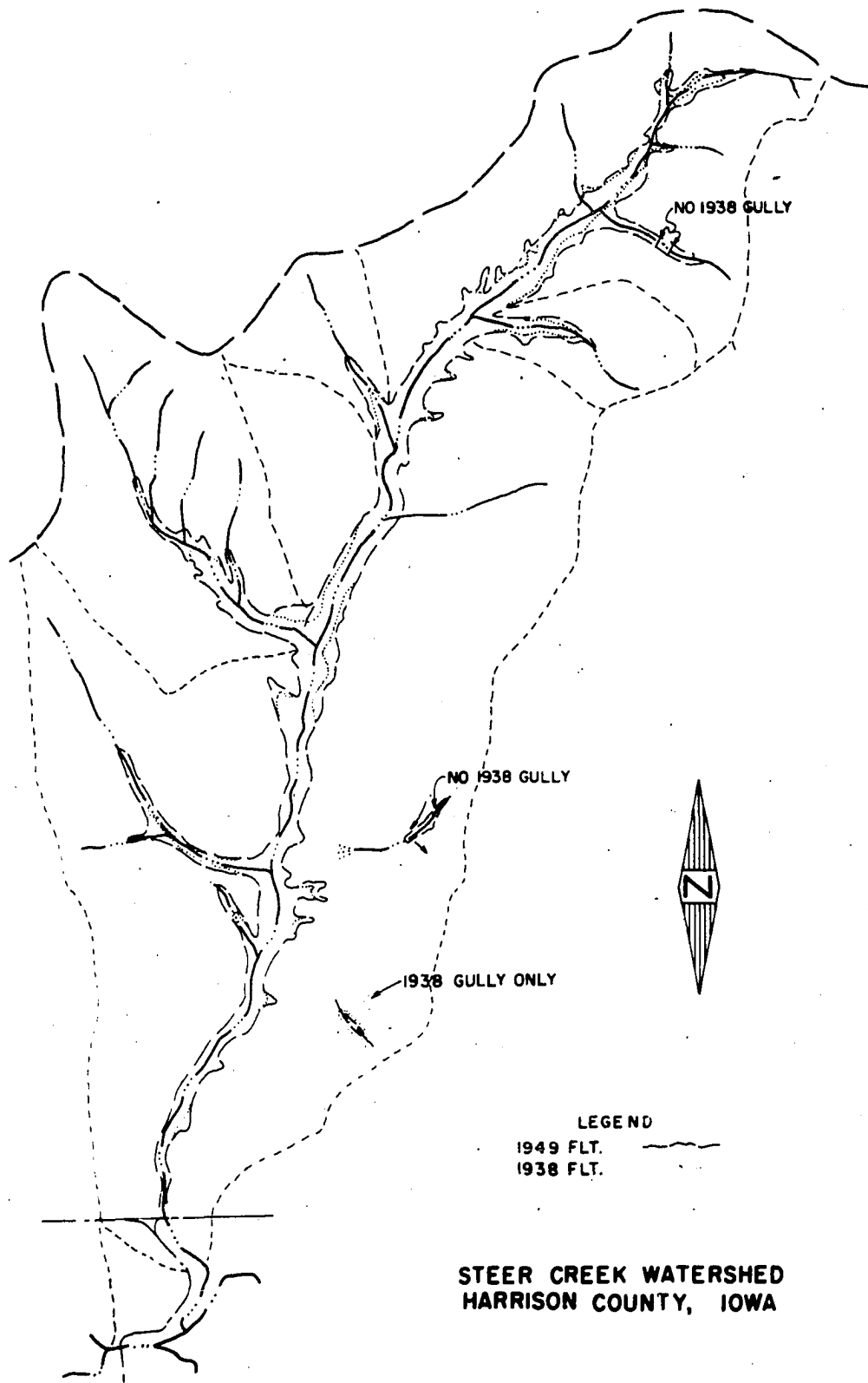


Figure 4. Map of lateral AB obtained by a Kelsh Plotter from 1938 and 1949 flights



data, however, were obtained from maps with a scale of 1 inch equal to 500 feet. This follows from the relatively small photographic scale for these flights.

Precipitation records

The choice of weather stations with appropriate precipitation records was limited. The nearest station to Steer Creek Watershed which had recording rain gage records prior to 1938 was the airport at Omaha, Nebraska. This weather station is approximately 40 miles from the watershed, but Shaw* indicated that in a 30-year period, differences in precipitation of the two locations would average out to be negligible. Therefore the precipitation records from Omaha were used in this study of gully development.

Interviews

Interviews with farmers who had been residents in the Steer Creek Watershed during the period from 1900 to 1930 were conducted by the author. From these interviews it was possible to correlate landmarks with stages of gully development in some areas during the period from 1900 to 1930. Further information on the stage of development of the drainage system in Steer Creek was obtained from the original land surveyors' notes taken during the year 1852.

*Shaw, Robert, Agronomy Department, Iowa State University, Ames, Iowa. Validity of precipitation records. Private communication. 1961.

Determination of Variables for Regression Analysis

The sources of information discussed under the heading, Methods of Obtaining Data, permitted the quantitative evaluation (directly or empirically) of the following factors:

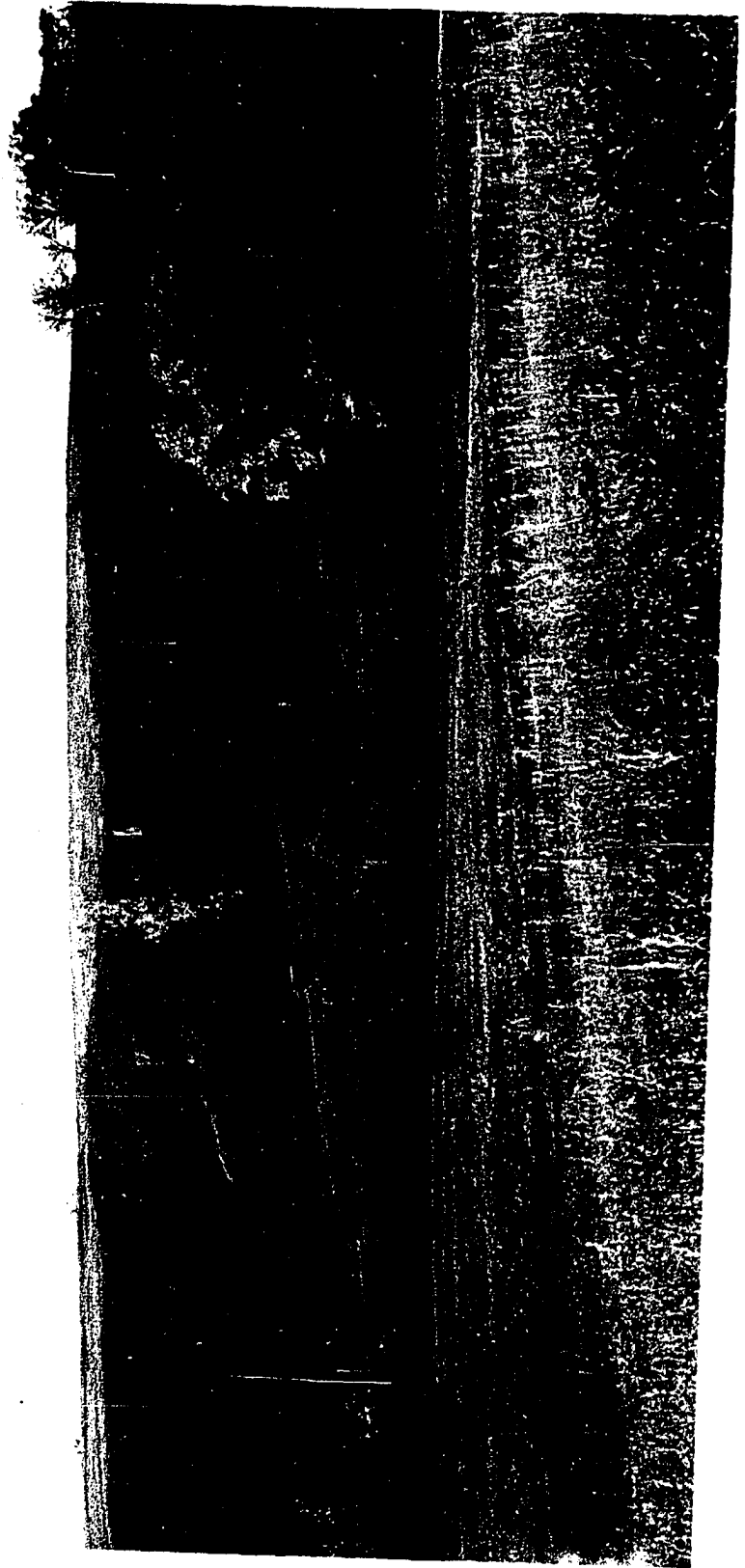
1. Gully surface area,
2. Gully length,
3. Drainageway length from outlet to watershed divide,
4. Gully width and cross section,
5. Depth and intensity of selected storm rainfall,
6. Antecedent precipitation index,
7. Volume of surface runoff,
8. Deviation of precipitation from long-time mean,
9. Land cover,
10. Watershed area, and
11. Area of watershed terraced.

The specific form or combination of the above factors which is used as a variable in the regression analysis, and detailed methods of evaluation are discussed for each factor in the following paragraphs.

Gully surface area

The rate of growth of a sample gully was determined by planimetering a map to obtain the area enclosed between the gully sides in the length from the outlet to the overfall. All the gullies in this study were continuous from the outlet to the overfall. It does not include the type of gully which begins and ends on the hillside as shown in Figure 5. The

Figure 5. A type of gully which begins and ends on the hillside



surface area was determined from the topographic maps for the years 1938, 1942, 1949 and 1961. Therefore if no apparent factors were found which would have altered the free growth of a gully, each gully provided three changes of surface area for periods of 4, 7 and 12 years. There were many instances, however, where the gully growth had been altered during one of the periods by road changes, construction of small earth fills or by having been filled in by the farmer. The time of occurrence of these practices could be determined from the aerial photos, and the gully growth during this period was not used in the study.

Figures 6 and 7 show examples where the gully growth has been altered. In Figure 6, point "a" indicates where the gully growth was stopped by a culvert through a road fill, and point "b" is an example of where the timber has been removed and the gully filled and reshaped. Figure 7 is an example of where an earth dam has been constructed and the gully reshaped below the dam.

Further difficulties were encountered in using the topographic maps from the 1938 and 1949 flights which were flown when trees were in full leaf. Timber growth along the sides of some gullies was present in 1938. The density of timber growth increased after 1938 to the extent that the Kelsh Plotter operator could not trace the exact outline of some of the gullies. The use of the smaller scale of the 1938 and 1949 flights combined with the timber growth resulted in instances where a gully showed a decrease in surface area when compared to the exact outlines on the 1942 and 1961 maps. Therefore some data were not usable. A comparison of the density of timber growth between 1938 and 1949 is shown for




Figure 6. Growth of a gully altered by road construction and gully
reshaping



Figure 7. Growth of a gully altered by earth dam construction



lateral AP in Figure 8.

Gully and watershed lengths

All flow lines within the gullies and in the drainageways above the overfall were plotted on the maps. All desired lengths were determined by the use of a map measure which records linear inches. The linear inches were adjusted according to the scale of the map. The following length factors were identified and measured from the maps.

L = Watershed length which is the length along flow line from outlet to the watershed divide.

L_1 = Length of gully along flow line from outlet to the overfall at the beginning of a period.

L_2 = Length of gully along flow line from outlet to the overfall at the end of a period.

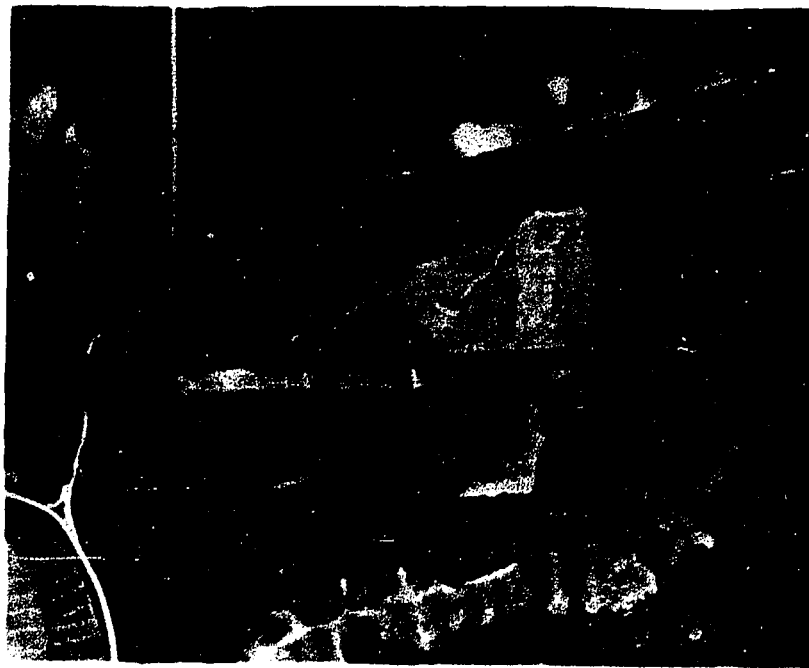
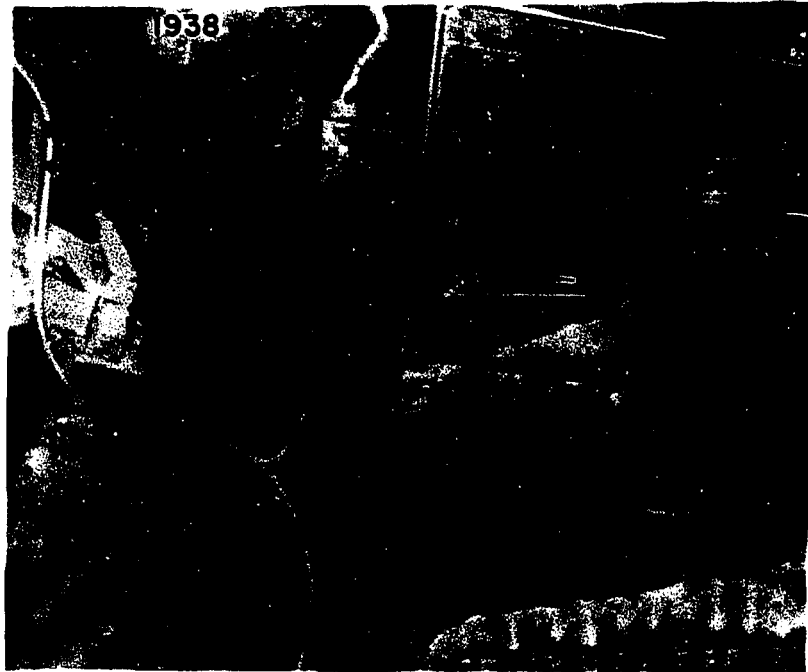
When used in a ratio, the lengths were combined to give a variable of the form L_1/L . A variable of this form was used for the following reasons.

1. The ratio is a measure of the amount of watershed area that contributes runoff at the overfall of the gully.
2. The ratio is a measure of the reduction in the time of concentration for the whole watershed relative to the watershed above the overfall.

Index of surface runoff

Since no runoff records exist for Steer Creek watershed, the surface runoff from selected storms was estimated and accumulated through each of the three periods to provide an index of runoff. A regression equation

Figure 8. Comparison of the timber growth on lateral AP for the years
1938 and 1949



for predicting runoff which was developed by Gray and Johnson (6) for the loess soil area of Iowa was used. The following equation predicts the runoff from a single storm.

$$X_1 = -0.100 + 0.177X_2 + 0.076X_3 + 0.0464X_6 + 0.118X_7 - 0.00175X_9$$

Where: X_1 = Volume of runoff in inches.

X_2 = Depth of rainfall in inches.

X_3 = Square of the depth of rainfall.

X_6 = Average intensity of principal burst in inches per hour.

X_7 = Antecedent precipitation index.

X_9 = Percent of watershed area in meadow (assumes little or no terracing).

The selected storms from the Omaha record within each period for which the runoff index was computed were those classified as intense storms by the United States Weather Bureau. The criterion used for classifying a storm as intense is given by the following equation:

$$d = 0.01t + 0.20$$

Where: d = inches of precipitation in time, t .

t = time in minutes.

Therefore if in any period of time during the storm, the depth equalled or exceeded the value given by the above equation, the storm was classified as intense. The runoff calculations were limited to those from intense storms because watershed research in the loess area has shown that storms of less intensity produce little runoff.

The antecedent precipitation index (API) was computed by the following power series:

$$API = \sum_{i=1}^7 (0.80)^i P_i$$

Where: P = Rainfall in inches on the i th day preceding the storm for which the runoff is to be computed.

The above formula shows that a period of 7 days was used to compute the API.

The vegetative cover and land use on Steer Creek Watershed were available for 1942 and 1961. In the runoff computations, the assumption was made that the 1942 land use was applicable for the period from 1938 to 1949 and the 1961 land use was applicable for the period from 1949 to 1961. Gray and Johnson (6) did not attempt to define the condition of the meadow. In this gully study, no rotation meadow or hay were included in the meadow variable. Only permanent pasture and timbered pasture were used. It is recognized that no snow melt was included in the runoff calculations. Also it was difficult to define the land cover and know with certainty its influence on runoff. However, it was felt that this method was the best available and gives an index of the surface runoff.

Deviation of precipitation from long-term mean

Precipitation depths which were above or below normal were assumed to affect gully development in two ways. A period of extremely low precipitation would reduce the density of vegetative cover which in turn would tend to increase the volume of runoff, other factors being equal. Similarly, periods of high precipitation would be conducive to luxuriant vegetative growth which would tend to reduce the volume of runoff for a given storm event. Another possible effect of precipitation above normal

would be to keep the soil in the vicinity of the gully at a high moisture content; thus the shearing resistance of the soil would be lowered and an increased rate of bank caving and overfall development would result.

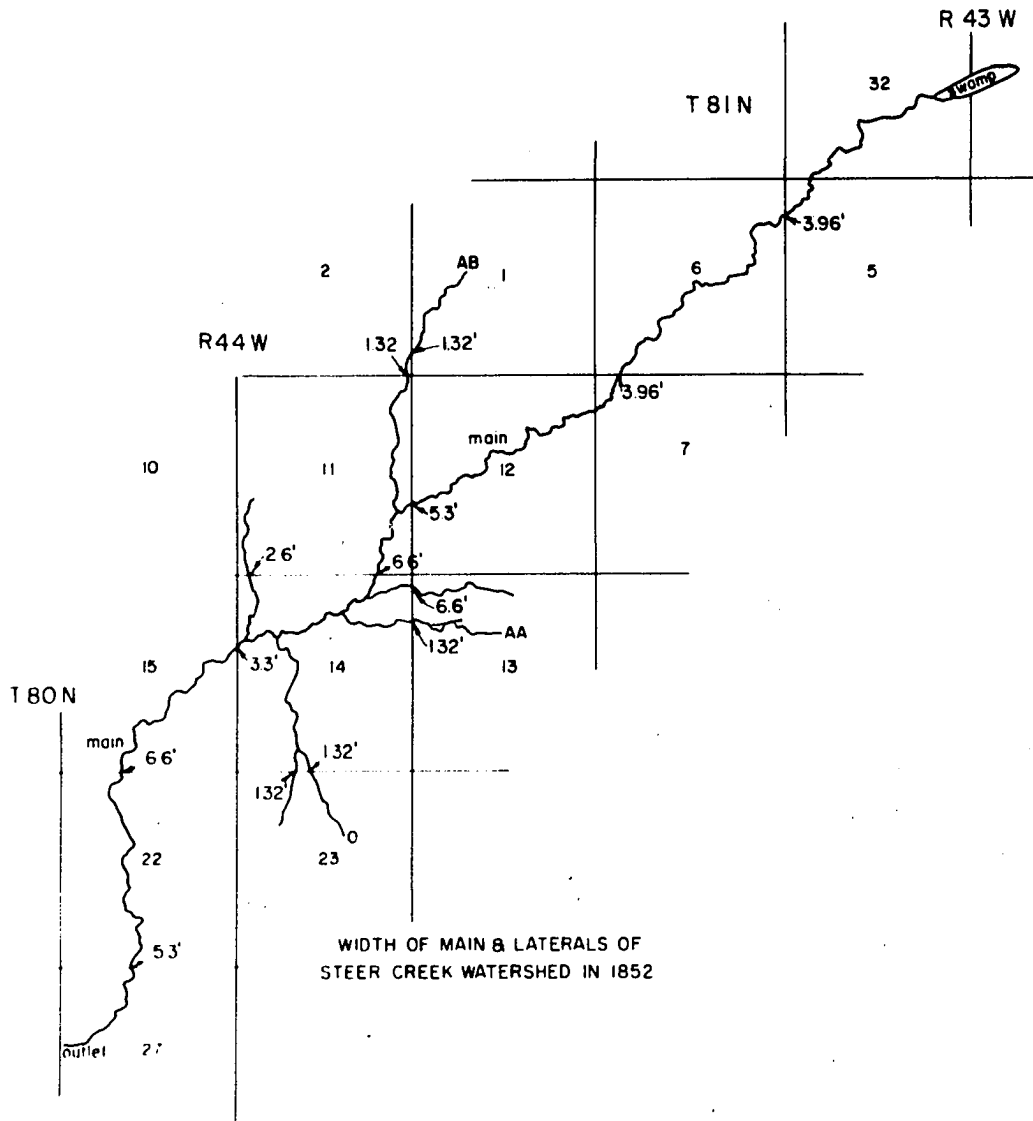
The deviations of precipitation from normal were computed for each of the months, April through October for each year from 1938 through 1960. The monthly deviations were algebraically summed for each year, and the yearly deviations were then summed for the 4-, 7- and 12-year periods which correspond to the periods for which the gully surface area change was evaluated. The records from the Omaha station were again used for total monthly precipitation.

ANALYSES

Development of Main and Lateral Gullies Prior to 1938

The original survey and section corner location for Steer Creek Watershed were made by Anderson (3), (4) in 1851 and 1852. In the original survey notes the location and width of the existing drainageways were given at the point where they crossed the section lines. The original notes show that Steer Creek originated from a swamp in the middle of Section 32, T 81 N, R 43 W. The original map, (Figure 9), which is in the Harrison County plat book (2) shows that Steer Creek followed much the same course as it does today with one major change from Section 14 to Section 11 (compare Figures 1 and 9). As Steer Creek main crossed Section 6 of T 80 N, R 43 W the width is shown to be approximately 4 feet. Farther downstream the main increased to a width of 5.3 feet as it crossed Section 11 of T 80 N, R 44 W, narrowing to 3.3 feet at Section 14 of T 80 N, R 44 W and reaching a maximum width of approximately 6.6 feet at the outlet. As shown in Figure 9, there were only five laterals from the main in 1851. It is possible to identify three of those laterals, which are well developed and exist today. They are laterals AB, AA and O. The remaining two laterals which are shown are not identifiable with any existing lateral today. The entire valley along Steer Creek was very marshy and boggy in the early days. It is possible that due to the change in course of the main since 1851 these laterals ceased to have an outlet and do not exist today. Therefore, there was no lateral gully development in 1851 and only small, defined

Figure 9. Map of Steer Creek Watershed showing drainage development
in 1852



drainageways for laterals AB, AA, O and for the two unidentified laterals.

Further information on the development of the main and lateral gullies between the original survey in 1851 and the first aerial photos in 1938 was obtained from interviews with elderly men who had lived in the Steer Creek Watershed all of their life. Two important points resulted from these interviews. All of those who were interviewed could remember when the Steer Creek main was no wider than that which was given in the 1851 survey. Further, due to the small channel capacity there was considerable flooding along the main during the period 1890 through 1930. During these periods of flooding there was considerable deposition of sediment in the main valley of Steer Creek. The best evidence of the development of the main was given by Mr. Erickson*. In 1932 at Station 171+88, where lateral O joins the main, Mr. Erickson buried a water pipe across Steer Creek main. The pipe was placed approximately 4 feet below the ground surface. Since 1932, erosion has exposed the pipe which is now 8 feet below the surface of the ground. In Figure 10 a 12-foot Philadelphia rod is on the water pipe at the west edge of the bank. This photograph was taken in October, 1961. At this location there has been approximately 4 foot of sedimentation in the valley since 1932. The photograph in Figure 11 shows the top of a 12-foot Philadelphia rod at the same elevation as the pipe in the east bank. The bottom of the rod is approximately 2 feet above the present (October, 1961) flow line.

*Erickson, Emil, Magnolia, Iowa. Verification of gully development. Private communication. 1961.

Figure 10. Depth and location of water pipe in west bank of main

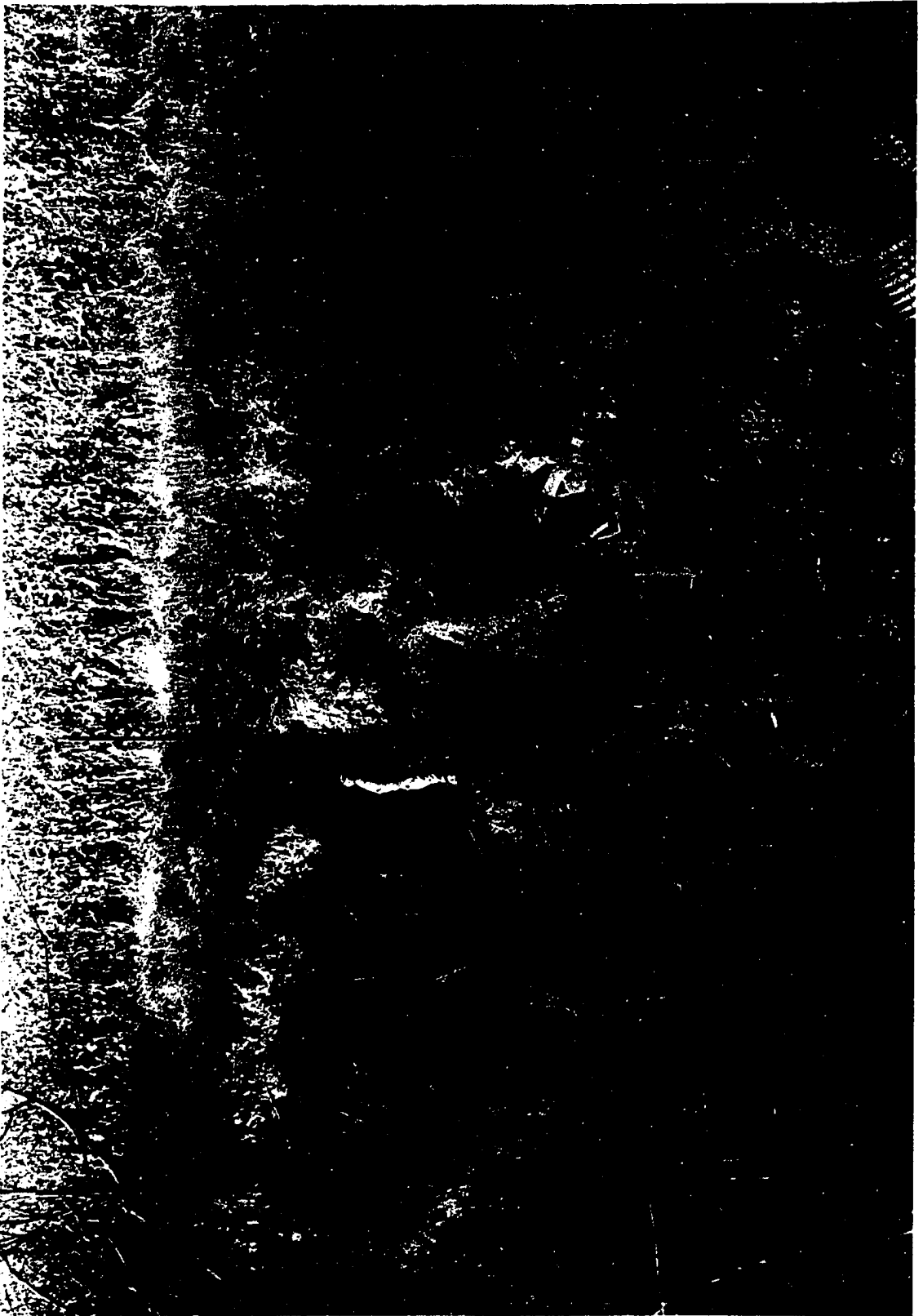


Figure 11. Location of water pipe in east bank of main



Therefore, it is evident that erosion has lowered the flow line at this point approximately 18 feet since 1932.

At Station 237+68 there was evidence to substantiate the fact that the depth of the main at that point was due to sediment deposits rather than a lowering of the original flow line. At Station 237+68, where lateral AA joins the main, the main is presently about 15 feet deep. At this station, Mr. Erickson* said that in 1890 to 1895 there was a 15-foot rise from the flow line of the main to the location of the Maule farm house. He could remember the difficulties encountered in taking a team of horses and loaded wagons across the main and up the hill into the farm lot. The valley is now level which indicates there has been approximately 15 feet of sedimentation. Thus the flow line of the main is now at about the same elevation as it was in 1900. This conclusion is further supported by the fact that the flow line of lateral AA has not deepened since 1900 at the point where it passes the Maule farm yard. This point is approximately 200 feet from its outlet into the main.

Mr. Block** gave essentially the same information on the development of Steer Creek main. He moved to a farmstead bordering the creek in July 1906. His farmstead is located at Station 190+86, which is approximately half way between where laterals O and AA join the main. He indicated that in 1935 they had used 20-foot stringers on a bridge to

*Erickson, Emil, Magnolia, Iowa. Verification of gully development. Private communication. 1961.

**Block, Herman, Magnolia, Iowa. Verification of gully development. Private communication. 1961.

span the creek at the farmstead. He did not remember the depth; however, he said that it was not too deep and that some of the width was necessary because of the wet, swampy conditions.

According to Mr. Fairchild*, further upstream between Stations 305+59 (junction of Lateral AQ) and 329+59 (junction of Lateral AX) the main was narrow and the valley generally swampy in 1905. He could remember when a team of horses and wagon could easily cross the main in this vicinity. Mr. Fairchild further indicated that the reach between Stations 305+59 and 329+59 had been dredged and straightened in 1944 to improve drainage.

Development of laterals

Mr. Erickson** said that in 1913 Lateral O could be farmed across at any portion. By 1942 it had developed into a very deep gully, and he indicated that it had started at the Steer Creek main and eroded upstream. The lower end of Lateral AA which junctions with Steer Creek main at the Maule farmstead has been relatively stable since 1900. Mr. Erickson said that the bridge at the lower end of Lateral AA (Station 2+50) had never been changed since 1900. The present plank bridge is 15 feet in length over a gully about 6 feet deep. However, in the upper portions of Lateral AA there was considerable gully development and active erosion in the period around 1900. Mr. Erickson said that as long as he could remember,

*Fairchild, Edward, Magnolia, Iowa. Verification of gully development. Private communication. 1961.

**Erickson, Emil, Magnolia, Iowa. Verification of gully development. Private communication. 1961.

it had required at least a 20 foot farm bridge to cross the gully at Station 44+50 on lateral AA. Mr. Block* who lived in the vicinity of lateral AA before moving to his present location indicated that this same farm bridge was approximately 30 feet long and that the gully was perhaps 30 feet deep in 1906.

Mr. Worth** said that the development of lateral AB was quite rapid. In 1905 it was possible to drive across lateral AB at a point approximately 10 rods upstream from the present county road fill. This road fill is at Station 46+82. He indicated that lateral AB had developed from the present road fill to near the ridge line in as short a period as possibly 10 years. He did say, however, that in 1905 there was a fairly deep gully at the present road fill.

Mr. Erickson*** picked corn in the watershed of lateral CX during the fall of 1915. At this time there was no gully development, and the lateral could be crossed at any point with a team and wagon. Immediately downstream from the junction of lateral CX and the main, county road N crosses the main. Mr. Erickson indicated that a small plank bridge was all that was necessary to cross the main at that point in 1915.

From the evidence in Figures 10 and 11 and personal interviews with farmers, it may be concluded that little change occurred on Steer Creek main between 1851 and 1906. Further, the major portion of the erosion in

*Block, Herman, Magnolia, Iowa. Verification of gully development. Private communication. 1961.

**Worth, E. O., Magnolia, Iowa. Verification of gully development. Private communication. 1961.

***Erickson, Emil, Magnolia, Iowa. Verification of gully development. Private communication. 1961.

the main has occurred since 1932. Several people have said that prior to 1932 it was easy to walk or drive a team across the main at three locations from Station 171+88 downstream to 0+00. As a result of flooding there has been deposition in the valley along the main; it is deeper at some locations than at others. It is apparent that around 1900 the gullies in laterals AA and AB were partially developed. Laterals O and CX have both developed into gullies since 1915.

Geomorphology of Gullies

The 1942 ground survey provided data to study the geomorphology of gullies. Two geometric relationships were investigated. They are as follows:

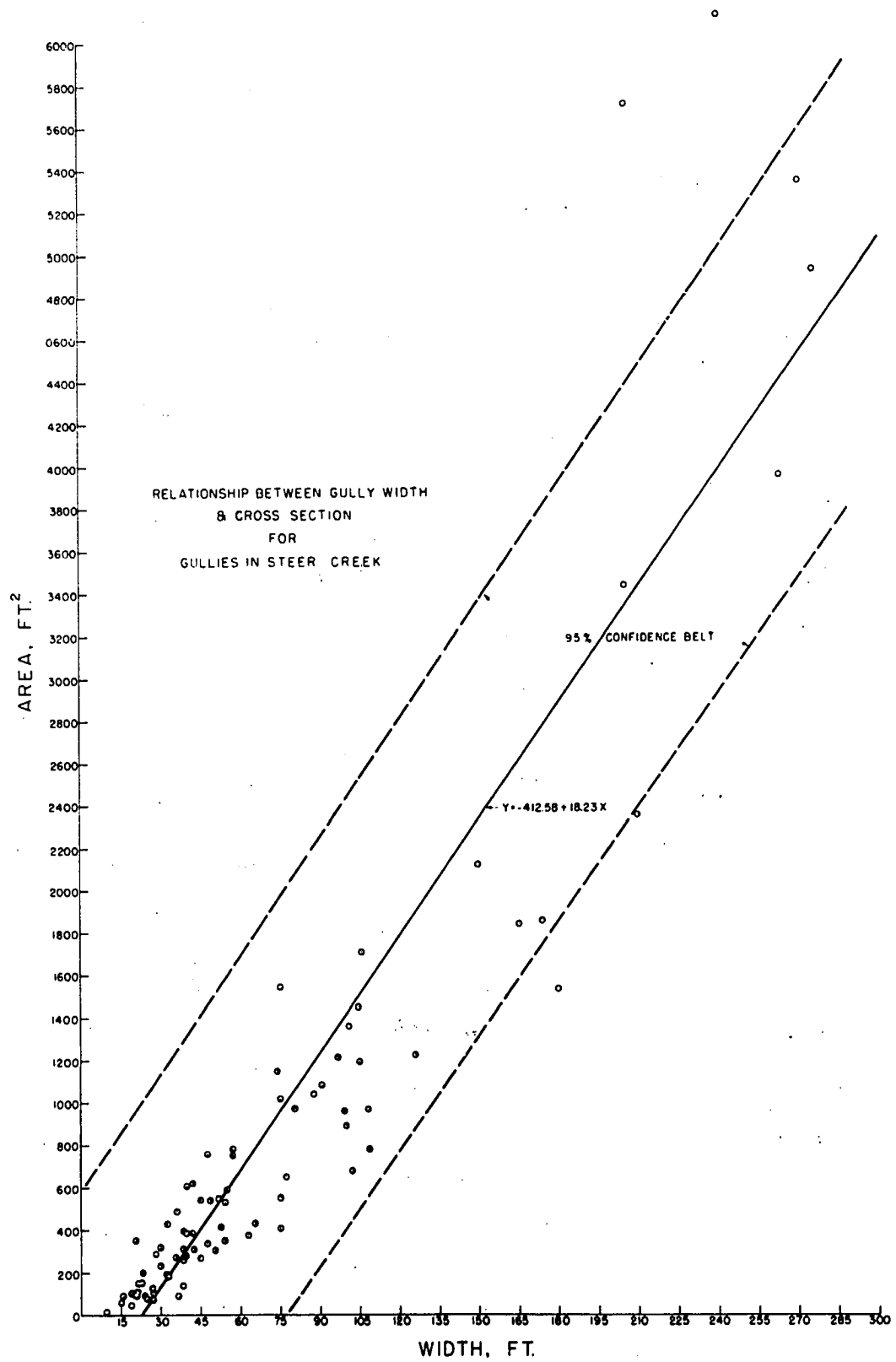
1. Cross-sectional area and depth as a function of top width,
2. Development of overfalls in the gully profile.

Relationships within the gully cross section

A functional relationship which relates the cross-sectional area of a gully to the top width would be of value in estimating the volume of land destroyed by gullying. This is true because the top width can be easily measured from aerial photos or with stadia whereas a cross-sectional survey is time consuming and difficult in deep gullies.

From a total of 85 cross sections which were made at locations on 16 lateral gullies and the main, the area was planimetered and the top width scaled from the plotted cross sections. A plot of the relationship between area and top width is shown in Figure 12. Two curves were fitted to the data. They were of the following form:

Figure 12. Relationship between gully width and cross section for gullies in Steer Creek Watershed



$$Y = a + bX + cX^2, \text{ and}$$

$$Y = a + bX.$$

where Y = cross-sectional area in square feet

X = top width in feet

a = constant

b, c = regression coefficients.

The equations of the fitted curves were as follows:

$$Y = -408.48 + 18.196X + 0.000152X^2 \quad (1)$$

$$Y = -412.58 + 18.234X \quad (2)$$

Equation 1 with the quadratic term does not appear to be significantly different from the linear relationship in Equation 2. However, Equation 1 was computed because a visual inspection of the data indicated an upward curving for the larger X values. A statistical test was made which gave the residual variation after fitting X as 13,135 out of a total of 111,348,754. On the basis of this statistical test, it was possible to omit the quadratic term. Thus Equation 2 was selected to represent the relationship and was drawn through the data as shown in Figure 12. The use of Equation 2 is limited to gully widths greater than 23 feet. This is not particularly serious as Figure 12 shows the majority of the gullies in the loessial area have widths greater than 30 feet. The 95 percent confidence interval for a predicted Y value, given a value of X, was computed and drawn on Figure 12. It may be noted that

all of the data except four points fall within this interval.

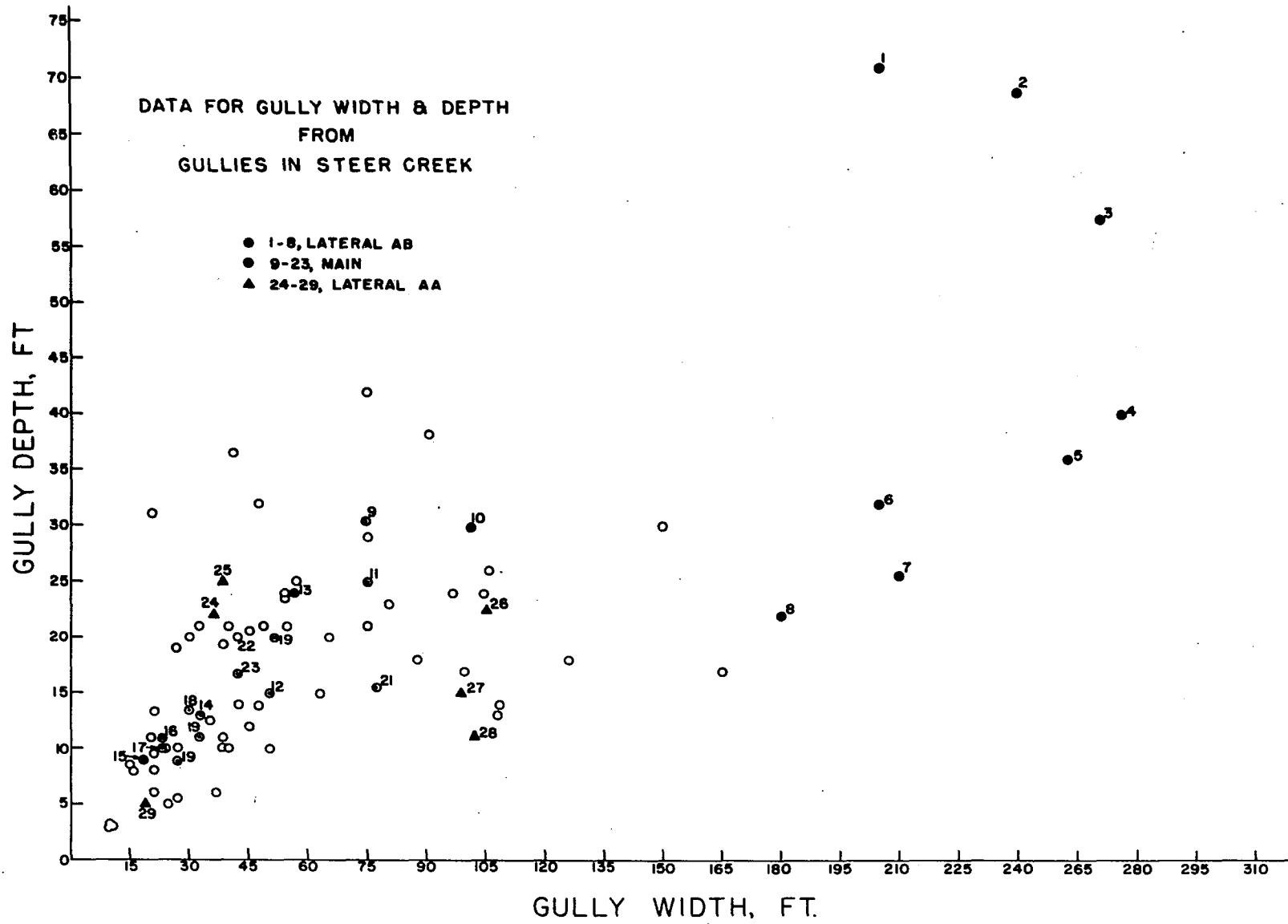
Design engineers who work in the loess soil region have expressed a belief that the gully width is directly related to the depth. Therefore the survey data which were used in the above analysis were used to determine the maximum depth of the gully at each cross section. A plot of the depth and width data is shown in Figure 13. No attempt was made to fit a curve to this data. There is some evidence that points 9 through 23, which represent the main, define a straight line relationship with a positive slope. However the two groups of points, 1 through 8 and 24 through 29, which represent laterals AB and AA respectively, show extreme scattering and indicate no relationship between depth and width. It was therefore concluded from the combined data of the laterals and the main of Steer Creek Watershed that no good functional relationship existed between the gully depth and width.

The results of the analysis on the geometrical relationships within gully cross sections suggest a pattern of gully development. Since only the cross-sectional area is related to the top width, the data indicate that the depth has been fixed by soil factors; thus an increase in top width increases the cross-sectional area as related in Equation 2.

Relationships within the gully profile

The 1942 profile survey of the laterals and main in Steer Creek Watershed revealed an extensive system of overfall development. The factors which cause the development of an overfall are not known, but the data provided information for the investigation of the following hypothesis.

Figure 13. Plotted data for gully width and depth from gullies in Steer Creek Watershed

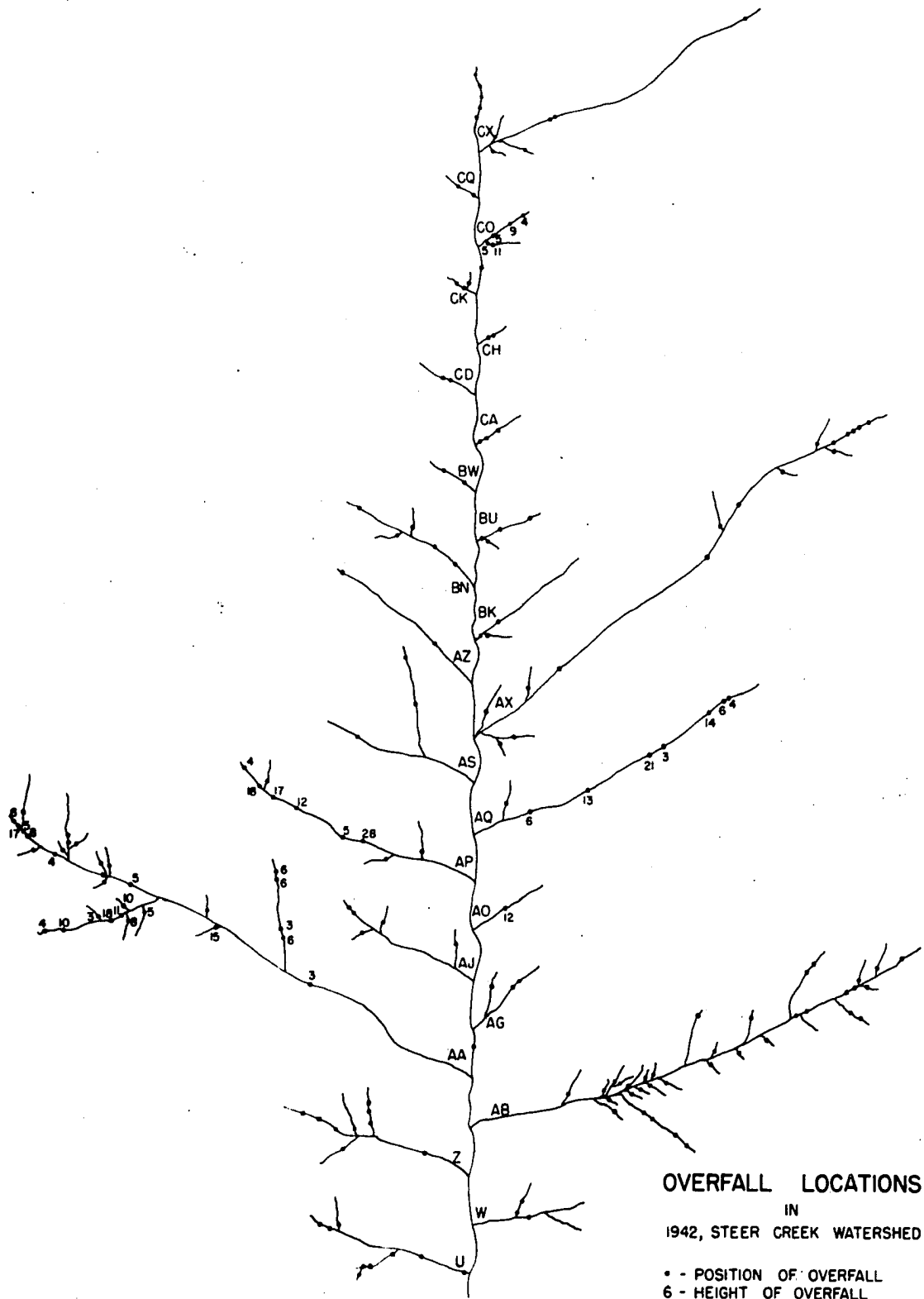


An overfall is started at the outlet of a lateral or sublateral when the flow-line elevation of the main or lateral respectively, is lowered.

The above hypothesis implies that the number of overfalls in a sublateral would be equal to the number in the lateral upstream from the point where the sublateral outlets into the lateral. This assumes that all overfalls advance and that none disappear by two overfalls combining into one. Figure 14 was drawn and shows the relative position of overfalls in 1942 in the main, laterals and sublaterals of Steer Creek. This figure is not a true map of the watershed as the laterals were simply alternated to the right and left for ease in spacing. However the lateral lengths and the position of the overfalls which are indicated by dots are drawn to scale. The sequence of the lateral outlets on the main are also the same as in the actual watershed. Figure 14 presents evidence which tends to reject the above hypothesis for most of the laterals. For example, in lateral AP, there are six overfalls with only one overfall in each of the first two sublaterals. A similar condition exists in laterals AX and Z. Only lateral CO has a pattern of overfall development which is in accordance with the hypothesis. Since there is not sufficient evidence to support the above hypothesis, the analysis suggests that sublateral gullies will develop independently of the overfalls in the lateral.

Generally, the older laterals have more sublateral development with a greater total number of overfalls. As indicated in Figure 9, laterals AA and AB existed in 1852. It is known therefore that they are the oldest and Figure 14 shows them to have the greatest number of overfalls. Figure 14 also shows the following items to be true.

Figure 14. Location and depth of overfalls in 1942 for gullies in Steer Creek Watershed



1. As the lateral or main becomes older and more developed, the overfalls are usually near the upper end. This is shown in laterals AB, AA, AX, AP and in the main.
2. The height of the overfalls in the laterals, which are shown by the numbers near the dots, follow no definite trend and appear to have a random value.

The profiles of the two oldest laterals, AB and AA, resembled a parabola when a curve was drawn along the flow line from the outlet, through the bottom of the overfalls to the ridge line. The similarity of the profile shapes suggested a possible relationship between the following factors:

1. Length from the outlet to the first overfall and the percent slope in the first reach, and
2. Total length and total elevation change from outlet to top of last overfall in the gully.

Figure 15 shows a logarithmic relationship between the length and slope of the first reach. The equation of the line fitted by least squares is

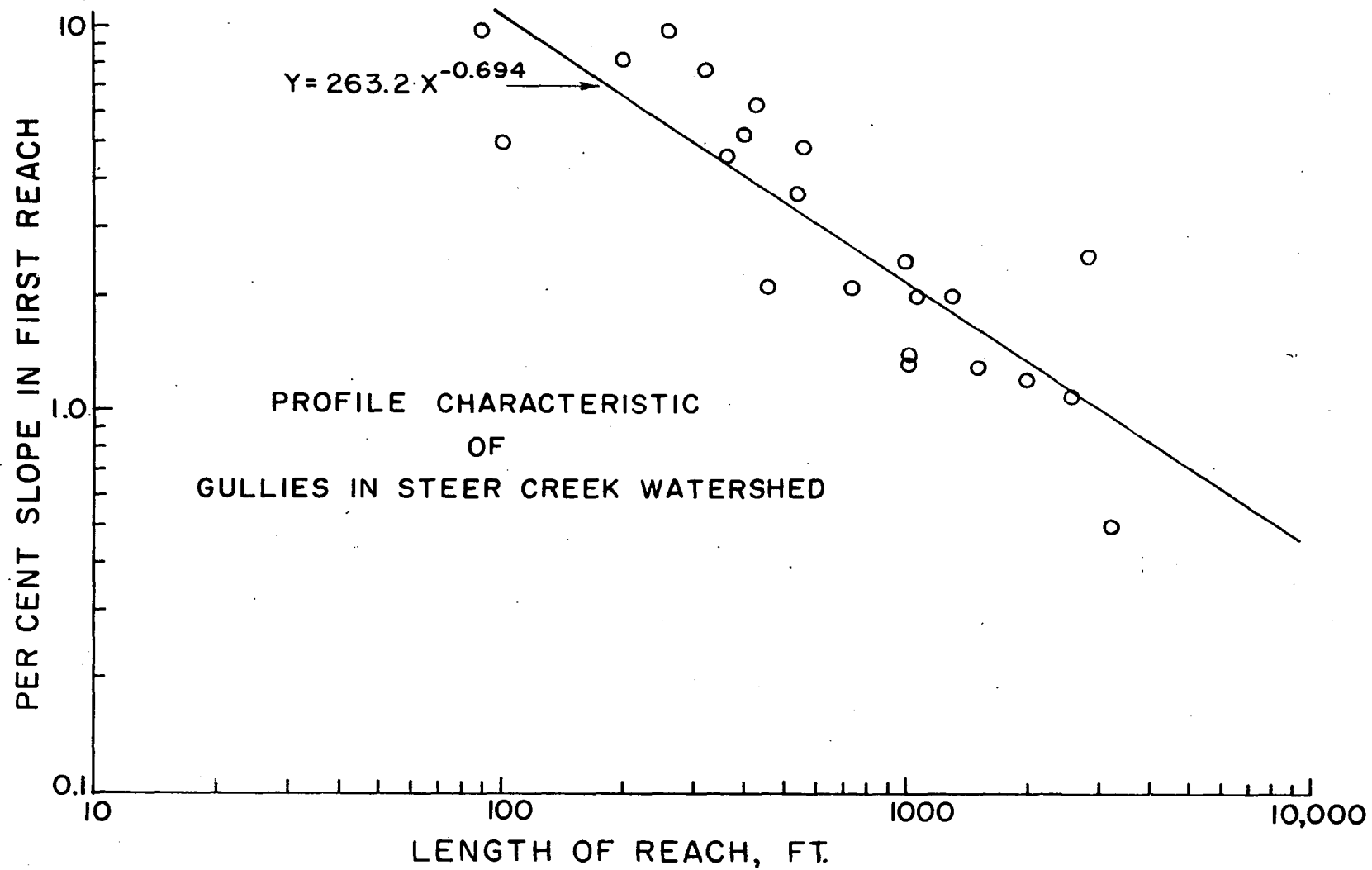
$$Y = 263.2X^{-0.694} \quad (3)$$

Where: Y = Percent slope in reach from outlet to first overfall.

X = Length of reach from outlet to first overfall in feet.

Equation 3 shows that the slope in the first reach of a gully tends to be flatter and more stabilized as the distance to the first overfall increases. This tendency was very evident in laterals AB and AA whereas

Figure 15. Logarithmic relationship between length and slope in the reach between the outlet and first overfall



in the younger gullies, where only one overfall exists near the outlet, the slope of the flow line is quite steep. The data in Figure 15 include 22 gullies in Steer Creek Watershed at different stages of development, therefore the use of Equation 3 is limited until data from gullies in related watersheds is included in the analysis.

The relationship between total length and elevation change to the last overfall is given in Figure 16. Due to the scatter of the plotted points no curve was drawn. However, a straight line relationship is suggested which indicates that as the total length of a gully increases the last overfall approaches the ridge line.

Development of Main Gully Since 1932

The depth, width and surface area of the main was obtained with varying degrees of accuracy for the years 1932, 1938, 1942, 1949 and 1961. The dense timber growth along the main made the 1938 and 1949 data of limited use in the derivation of a functional relationship for the growth of the main. However, from the remaining data it was possible to determine whether the change in depth and width during the period from 1932 to 1961 was linear or curvilinear.

Rate-of-width change

The data shown in Table 2 permitted an investigation of the change in the width of the main gully during the period 1932-61. All of the 1932 values were estimated from interviews, but the 1942 and 1961 figures are correct. It is noted that at some stations the 1938 and 1949 widths were nearly as large or larger than the width for the succeeding year.

Figure 16. Data for total length and change in elevation to last overfall in gully

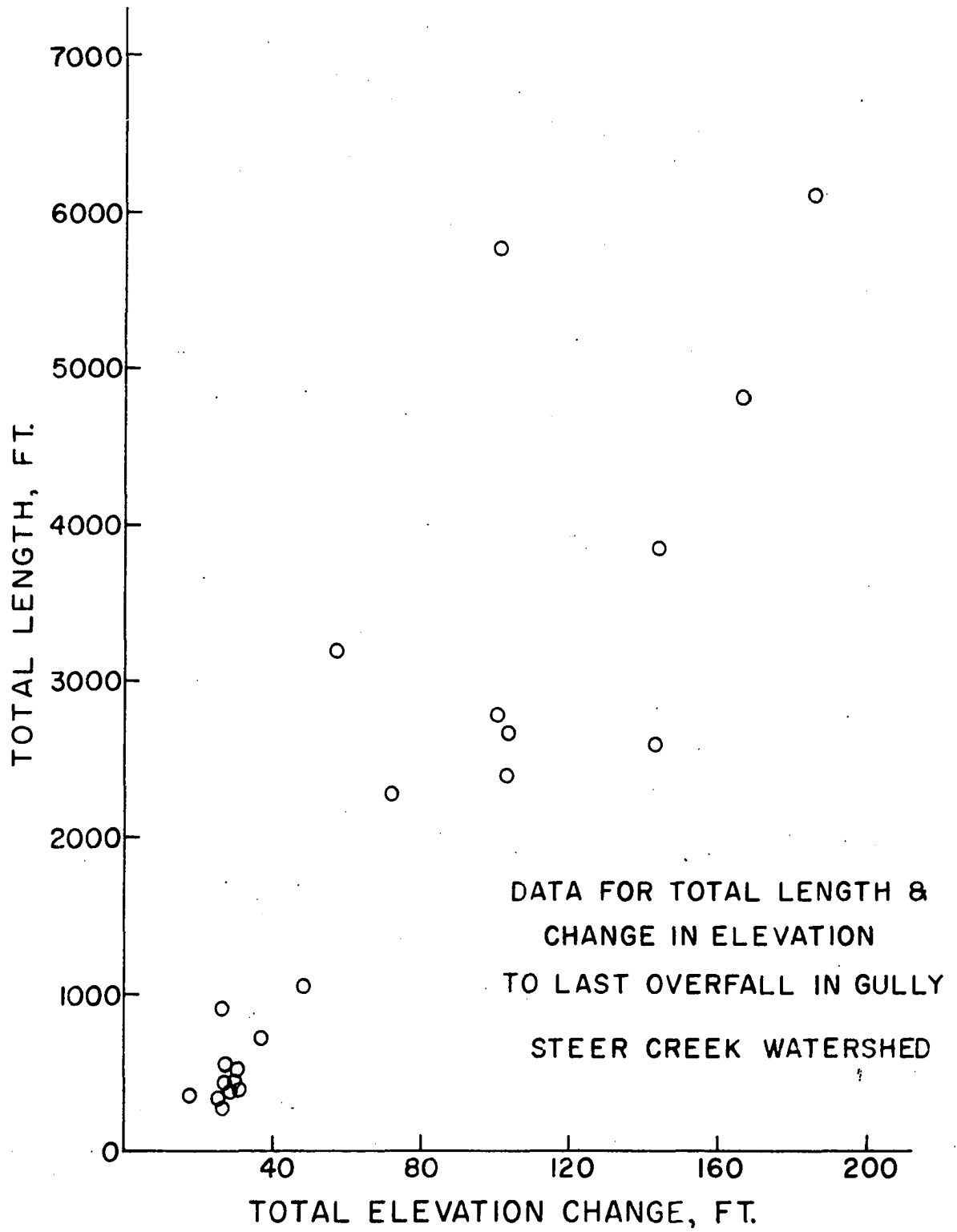


Table 2. Top width of Steer Creek main at selected stations during period from 1932 to 1961

Station	Top width, ft.				
	1932	1938	1942	1949	1961
6+10		35	35	45	55
60+79		35	42	45	55
104+20	6-8 ^a	40	42	60	58
144+00		50	52	52	55
172+29	6-8 ^a	--b	--b	--b	50
190+86	15-18 ^a	--b	--b	--b	50
264+24		35	32	50	40
440+58		40	74	65	148
469+12		95	101	110	185
Average	15 ^c		54		85

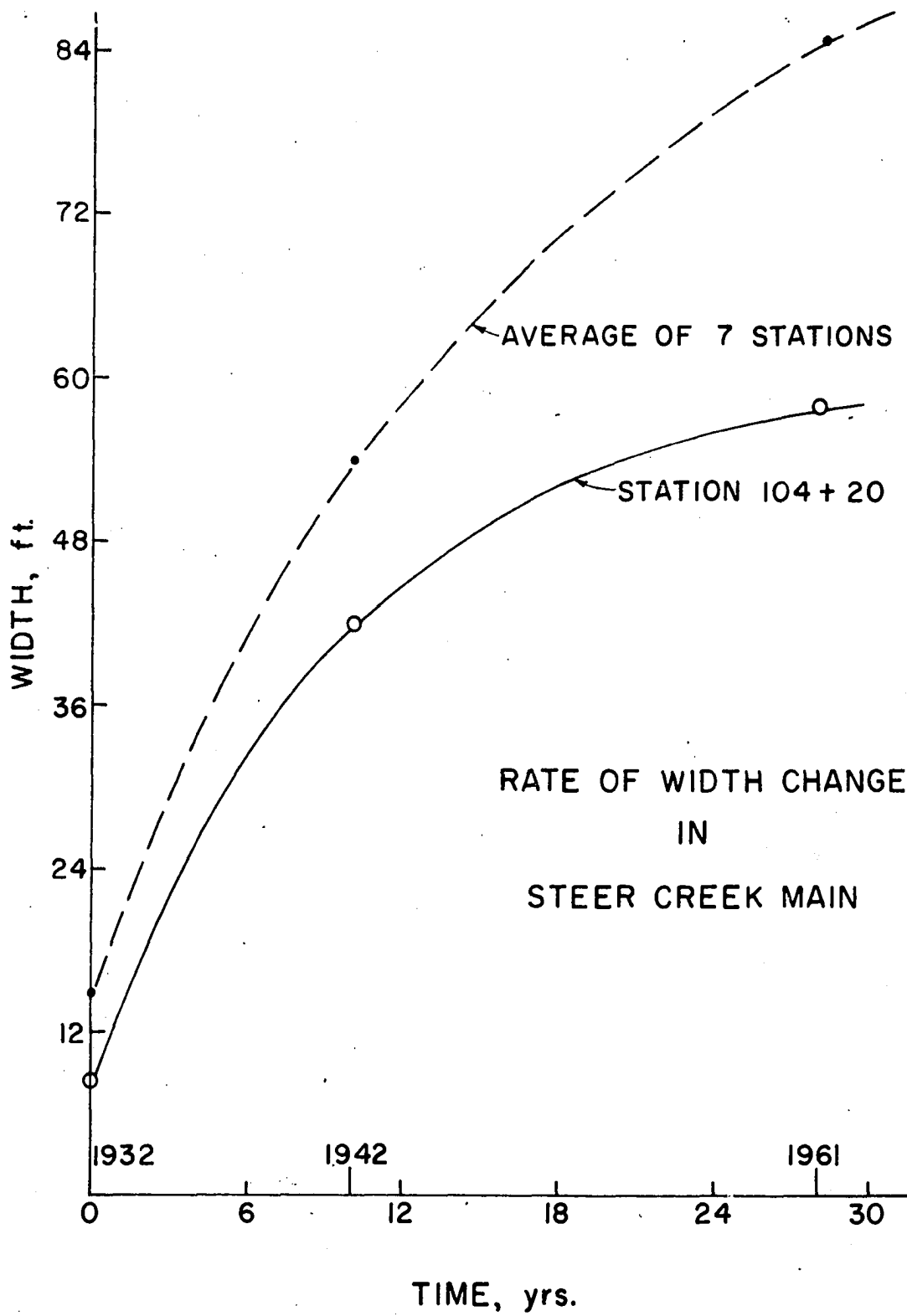
^aObtained by interview.

^bData not available for these years.

^cEstimated.

This resulted because the Kelsh Plotter operator followed the timber line rather than the exact gully outline. The rate of change in width for station 104+20 is shown in Figure 17. The average of seven stations is also shown in Figure 17. The curves drawn through three points indicate a curvilinear change in width with time for the 38-year period, and that the rate of growth in width is reducing with time. The observations may be fortuitous due to the lack of data.

Figure 17. Rate-of-width change in Steer Creek main



Rate-of-depth change

Values of the depth, which were obtained at locations where bridges span the main, permitted an investigation of the change in depth of the main gully. These data are shown in Table 3. The distance from the flow line to the low bridge steel was obtained from the 1942 ground survey.

Table 3. Depth of Steer Creek main at selected stations during period from 1932 to 1961

Station	Depth, ft.		
	1932	1942	1961
6+10		13.6	17.5
98+78	2-4 ^a	16.6	30.3
156+95		15.2	26.8
172+29	2-4 ^a	21.0	27.5
190+86		16.4	25.5
225+28		11.3	13.0

^aObtained by interview.

The corresponding distances were measured in 1961. The only reliable depth measurement for 1932 is at Station 172+29 where the water pipe shown in Figure 11 crossed the main. The data for this station show a slower rate of depth change between 1942 and 1961 than in the period from 1932 to 1942. However, there is not sufficient data to establish a curve for the rate-of-depth change.

Development of Lateral Gullies Since 1938

The major portion of this study was devoted to fulfilling the second objective which was to relate gully growth to hydrologic, gully geometry and topographic variables. Regression analysis was used to derive a relationship between variables associated with gully development.

Williams (13, p. 1) implies that in a normal experiment, a mathematical model is formulated and then the concordance of the model is tested in all respects with the data. He further states that

Regression analysis is a means of making such an interpretation when the expected value of one variable is defined as a function of the observed values of other variables. Many physical laws, both theoretical and empirical, are of this nature when it can be assumed that, for practical purposes, the variables are observed without error. However, in the biological sciences, and indeed in all the sciences wherein the possibility of errors of observation is admitted, the idea of a relationship among errorless quantities turns out to be otiose, whereas the regression concept which bases relationships on the quantities actually observed proves to be exceedingly useful.

Since regression analysis may be defined as the estimation or prediction of the value of one variable from the values of other given variables, the practical application presents a number of problems. First there are the problems of estimating the constants of a regression when the form of the relationship is given and the testing of the concordance of some preassigned regression relation with the data. There is also the question of which variables should be included in the relationship.

The functional relationship or model for predicting gully growth and the variables which should be included were not known prior to this

study. Therefore, a model which expressed gully growth as a linear function of the variables was assumed for the preliminary analysis.

Regression analysis with linear model for change in gully area

A regression analysis was made on the data from the 61 samples which are given in Table 8 of Appendix A. The equation which was derived from this analysis predicted the change in the surface area of a gully for given values of the variables appearing on the right side of the equation. Since the model was assumed to be linear, the predicted change in surface area equals a constant plus the sum of the products of all variables and their respective coefficients.

Table 4 includes five equations which were derived by using the linear model. These equations were obtained by programing the data in Table 8 for the IBM 650 computer. With the use of a computer, it is relatively easy and economical to vary the number and combination of the variables appearing on the right side of the equation. Thus five combinations of variables represented by Equations 4, 5, 6, 7 and 8 in Table 4 were investigated.

On the basis of statistics, the equations in Table 4 fit the data reasonably well. The R^2 statistic, which according to Snedecor (12) measures the fraction or percent of total deviation which is attributed to regression, is 0.70, 0.89, 0.73, 0.89 and 0.89 respectively for Equations 4, 5, 6, 7 and 8. There is, however, an opportunity to be misled by the value of the R^2 statistic. The values of the dependent variable which are the greatest distance from the mean contribute more to the R^2 value than those values near the mean. An inspection of the data

Table 4. Regression equations to predict change in gully area using a linear model^a

No.	Equations
4	$X_1 = -0.906 + \underline{0.0022}X_2 - \underline{0.0484}X_3 + 0.0098X_4 + 0.0308X_5 - 0.0271X_6 + \underline{5.5209}X_7$
5	$X_1 = -0.324 - 0.0006X_2 - \underline{0.0435}X_3 + 0.0063X_4 + 0.0453X_5 - \underline{0.0355}X_6 + 0.0013X_8 - 0.00008X_9$
6	$X_1 = -1.665 - 0.0019X_2 - \underline{0.0495}X_3 + 0.0143X_4 + 0.0431X_5 - 0.0814X_6 + \underline{5.5576}X_7 + \underline{0.0003}X_9$
7	$X_1 = -0.526 - 0.0017X_2 - \underline{0.0465}X_3 + 0.0069X_4 + \underline{0.0533}X_5 - 0.0506X_6 - 0.2172X_7 + \underline{0.0013}X_8$
8	$X_1 = -0.240 - 0.0428X_3 + \underline{0.0057}X_4 + 0.0443X_5 - 0.0286X_6 + \underline{0.0012}X_9 - \underline{0.0013}X_{14}$

Where: X_1 = Change in gully surface area (Ac)

X_2 = Watershed area (Ac)

X_3 = Deviation of precipitation from normal (In)

X_4 = Index of surface runoff (In)

X_5 = Length of period (Yr)

X_6 = Terraced area of watershed (Ac)

X_7 = Ratio of gully length, L_1 , at beginning of period to total length, L , from outlet to watershed divide

X_8 = Gully length, L_1 , at beginning of period (Ft)

X_9 = Total length, L , from outlet to watershed divide (Ft)

X_{14} = Length from end of gully to watershed divide (Ft)

^aThe underlined coefficients in this table indicate a significant level of 95 percent or greater.

in Table 8 of Appendix A shows that most samples have a change in surface area less than 1.00 acre, but one sample has a value of 9.4 acres. A calculation shows that the later sample contributes approximately 0.30 to the value of R^2 . Thus if the sample value with a change in surface area of 9.4 acres were erroneous, the regression could be misleading. However, the author knows of no reason to doubt the validity of this sample. Each regression coefficient of the variables in Equations 4, 5, 6, 7 and 8 was tested to determine if the value was significantly different from zero. This test of significance is based on the t-distribution, and in a given equation considers a regression coefficient to be tested independently of the remaining coefficients. Those coefficients which were significant at the 95 percent level or greater are shown in Table 4 by underlining the coefficient. The failure of a regression coefficient to be significant does not necessarily mean that the associated variable should be omitted from the equation. Yates, as quoted by Williams (13, p. 5), has the following to say about tests of significance.

The emphasis on tests of significance, and the consideration of the results of each experiment in isolation, have had the unfortunate consequence that scientific workers have often regarded the execution of a test of significance on an experiment as the ultimate objective. Results are significant or not and that is the end of it. Research workers, therefore, have to accustom themselves to the fact that in many branches of research the really critical experiment is rare, and that it is frequently necessary to combine the results of numbers of experiments dealing with the same issue in order to form a satisfactory picture of the true situation.

The use of a test of significance as the only criterion for elimination of variables is not considered wise by Fuller*, a statistician on the

*Fuller, Wayne, Dept. of Statistics, Iowa State University, Ames, Iowa. Rejection of variables by tests of significance. Private communication. 1961.

staff of Iowa State University. If sound judgment on the part of the experimenter indicates a variable should be included in the regression equation, Fuller believes it should be included even though its coefficient is not significant and possibly omitted when the sign of the coefficient is not in accord with the expected result.

On the basis of the preceding discussion, there is no evidence to reject any of the equations in Table 4. However, two of the variables which have negative coefficients require an explanation. The negative coefficient for the deviation of the precipitation from normal, X_3 , possibly can be explained by the following observation. Shrader* has observed large cracks in the soil in the loess soil areas during extremely dry periods. Shrinkage cracks which form parallel to the gully sides would intercept surface runoff and would tend to increase the rate of gully bank caving. It is noted also that the signs for the coefficients of the watershed area variable, X_2 , and the variables which include watershed lengths, X_7 and X_9 , alternate between positive and negative. Logically, an increase in watershed area would increase gullying and therefore should have a positive sign. Apparently the inclusion of the watershed length variable which is correlated with the watershed area removes some of the effect of the watershed area with the result that it appears with a negative sign. The signs of the coefficients for the remaining variables are as would be expected.

*Shrader, William, Department of Agronomy, Iowa State University, Ames, Iowa. Cracks in loess soil during dry weather. Private communication. 1961.

A further check on the validity of Equations 4, 5, 6, 7 and 8 was made by substituting the original data into the equations and examining the predicted value of change in gully surface area. All equations gave some predicted values which were negative or less than zero. This result is not desirable and limits the usefulness of the linear model equations.

Regression analysis with logarithmic model for change in gully area

The preliminary analysis with the assumption of a linear model did not give satisfactory results and showed that a model should be used which would not permit negative predicted values. Also, computations from the linear analysis revealed correlations of 0.80 to 0.92 between the following variables:

1. Watershed area and watershed length,
2. Length of period and index of surface runoff, and
3. Length of period and deviations of precipitation from normal.

Therefore, a logarithmic model with different variable combinations was tried. This would force the curve through the origin and no negative predicted values would result from the use of the equation. In the logarithmic model, the logarithm of the predicted variable equals the logarithm of a constant plus the sum of the products of the coefficients times the logarithms of the respective variables. Since the variable, X_3 , which represented the deviation of precipitation from normal could be either positive or negative, it was not possible to include this variable in the logarithmic form; the product of X_3 and its

coefficient was added to the logarithmic terms. Thus after taking the anti-logarithm of both sides of the model, the equation is of the form represented by Equations 9, 10 and 11 in Table 5.

With the information gained from the linear analysis, the combinations of variables for the logarithmic model were chosen to satisfy the following conditions:

1. One variable would be used to measure the watershed area contributing runoff at the uppermost overfall.
2. One variable would be used to measure the length along the gully where growth in surface area results from increased width in the present length of the gully.
3. A lesser number of variables would be used to measure the hydrologic and period of time factors.
4. The remaining variables would be the same as in the linear analysis.

Although the R^2 values for Equations 9, 10 and 11 are lower than for the linear model equations, most of the coefficients have the correct sign as may be noted in Table 5. The watershed area variable becomes positive in Equation 9 with the omission of the watershed length variable. However, the sign is reversed in Equation 11. An increase in total watershed area would increase the surface area change in Equation 9 whereas the opposite would occur in Equation 11. The only difference in variables between Equations 9 and 11 is that in Equation 9 the period of time, X_5 , was used in lieu of the runoff index, X_4 . With a high correlation between X_4 and X_5 , the change in sign for the watershed area would

Table 5. Regression equations to predict change in gully area using a logarithmic model^a

No.	Equations
9	$X_1 = 0.013 X_2^{0.0790} X_5^{\underline{1.314}} X_6^{-0.0708} X_{10}^{\underline{0.500}} e^{\underline{-0.0783}X_3}$
10	$X_1 = 0.01 X_4^{0.0982} X_6^{-0.0440} X_8^{\underline{0.7954}} X_{14}^{-0.2473} e^{-0.0360X_3}$
11	$X_1 = 0.549 X_2^{-0.1314} X_4^{0.0411} X_6^{-0.0575} X_{10}^{\underline{0.6775}} e^{-0.0304X_3}$

Where: X_1 = Change in gully surface area (Ac)

X_2 = Watershed area (Ac)

X_3 = Deviation of precipitation from normal (In)

X_4 = Index of surface runoff (In)

X_5 = Length of period (Yr)

X_6 = Terraced area of watershed (Ac)

X_8 = Gully length, L_1 , at beginning of period (Ft)

X_{10} = Gully surface area at beginning of period (Ac)

X_{14} = Length from end of gully to watershed divide (Ft)

e = 2.71828 (Base of natural logarithm)

^aThe underlined coefficients in this table indicate a significance level of 95 percent or greater.

not be expected. Since this result is not explainable, Equation 10 is preferred over Equations 9 and 11. In Equation 10 the length from the overfall to the watershed divide has been used to measure the effect of the watershed area above the overfall; this watershed area contributes runoff for the elongation of the gully. The gully length, X_8 , has been included in Equation 10 which is a measure of the watershed area contributing runoff to the perimeter of the gully. This length also gives an indication for potential gully growth through widening of the gully. With an increase in area terraced, the terrace variable reduces the gully surface area. This would be expected since level terraces reduce the volume of runoff. The two remaining variables, X_{14} and X_3 , are both negative. Every regression which has been made in the gully study shows X_3 to be negative. The reason for its negative sign is the same as in the case of the linear models. The variable for the length from the gully overfall to the watershed divide with its negative sign is a subtractive factor which reduces the effect of X_8 when the gully is starting. As the gully length, L_1 , increases, the value of X_{14} increases and approaches a maximum value equal to one.

The decision of which model fit the original data best was made on the basis of the computations in Table 6. In Table 6 the values of the predicted gully surface area change, obtained when the original data were substituted into a given equation, are subtracted from the sample value, Y . The deviations, $Y - \hat{Y}$, are shown for the four equations. In the last four columns this deviation is shown as a percent of the sample value, Y . For example, the value of 50 percent for lateral U under Equation 10

Table 6. Comparison of the difference between the predicted gully surface area change, \hat{Y} , and the surface area change of the sample, Y , for Equations 8, 9, 10 and 11

Lateral	Y (Ac)	Deviations, $Y - \hat{Y}$ (Ac)				$(Y - \hat{Y})/Y \times 100$			
		Equation no.				Equation no.			
		8	9	10	11	8	9	10	11
0	3.10	0.207	0.750	1.570	1.690	6.0	24	51	55
0	0.28	0.151	0.403	0.040	0.090	54.0	140	14	31
0	2.24	0.220	1.070	1.130	1.499	9.0	44	46	61
U	0.04	0.169	0.005	0.020	0.007	400.0	13	50	17
U	0.07	0.574	0.015	0.003	0.016	800.0	22	4	230
U	0.03	0.320	0.075	0.101	0.060	1000.0	250	336	200
U-2	0.11	0.038	0.071	0.088	0.069	34.0	65	80	63
U-3	0.16	0.241	0.061	0.070	0.054	150.0	38	44	34
W-3	0.14	0.030	0.101	0.118	0.097	21.0	72	84	69
W	0.12	0.202	0.319	0.107	0.064	170.0	265	89	53
Z-1	0.18	0.458	0.098	0.135	0.022	250.0	54	75	12
Z	4.07	0.267	2.510	2.220	3.030	6.5	61	54	74
AB-6	1.00	0.420	0.048	0.480	0.464	42.0	48	48	46
AB-16	1.60	0.176	0.040	0.806	0.340	11.0	25	50	21
AB-16	1.50	0.072	0.857	0.786	0.420	4.8	57	52	28
AB-20	0.60	0.150	0.101	0.200	0.256	25.0	17	33	42
AB-20	0.60	0.136	0.330	0.224	0.154	23.0	55	37	25
AB-22	0.60	0.507	0.306	0.089	0.192	84.0	52	15	32
AB	9.40	0.638	3.150	5.020	4.340	6.8	33	53	46
AX-9	0.29	0.239	0.154	0.178	0.171	82.0	53	61	59

Table 6. (Continued)

Lateral	Y (Ac)	Deviations, $Y - \hat{Y}$ (Ac)				$(Y - \hat{Y})/Y \times 100$			
		Equation no.				Equation no.			
		8	9	10	11	8	9	10	11
AX-10	0.36	0.135	0.173	0.180	0.237	37.0	48	50	66
AX	0.41	0.060	0.228	0.257	0.288	14.0	56	63	71
AX	2.47	1.060	1.380	1.526	1.010	43.0	56	62	41
AX	0.51	0.821	0.327	0.171	0.790	160.0	63	33	152
AX	0.45	1.986	0.548	0.321	0.680	440.0	120	71	150
AZ	0.86	0.196	0.100	0.382	0.307	22.0	12	44	35
AZ	0.07	0.037	0.127	0.145	0.207	53.0	184	210	300
AZ	0.48	0.430	0.291	0.320	0.287	89.0	61	67	60
BL	0.08	0.178	0.014	0.028	0.015	220.0	18	35	19
CA	0.12	0.006	0.021	0.001	0.019	5.0	21	1	19
CA	0.22	0.219	0.120	0.008	0.080	100.0	52	4	35
CD	0.27	0.108	0.083	0.037	0.032	40.0	31	14	12
CH	0.08	0.179	0.021	0.104	0.049	220.0	26	130	61
CH	0.05	0.146	0.044	0.133	0.097	290.0	88	266	194
CK	0.18	0.251	0.034	0.059	0.014	140.0	19	33	8
CO	0.22	0.318	0.078	0.251	0.303	140.0	35	114	138
CO	0.27	0.050	0.001	0.081	0.139	18.5	1	30	52
CX	1.20	0.431	0.306	0.471	0.110	36.0	25	39	9
AA-1	1.54	0.551	0.964	0.330	0.626	36.0	61	21	40
AA-1	0.50	1.346	0.198	0.146	0.150	270.0	39	29	30
AA-1a	0.42	0.683	0.347	0.347	0.375	163.0	83	83	90

Table 6. (Continued)

Lateral	Y (Ac)	<u>Deviations, $Y - \hat{Y}$ (Ac)</u>				<u>$(Y - \hat{Y})/Y \times 100$</u>			
		Equation no.				Equation no.			
		8	9	10	11	8	9	10	11
AA-2	0.04	0.227	0.113	0.066	0.085	560.0	283	165	212
AA-5	0.13	0.001	0.034	0.038	0.028	0.1	26	29	21
AA-5	0.09	0.439	0.378	0.186	0.200	480.0	420	207	222
AA-10	0.50	0.187	0.289	0.293	0.000	37.0	58	59	0
AA-12	0.02	0.208	0.087	0.105	0.104	1000.0	290	350	317
AA	0.23	0.279	0.023	0.119	0.072	120.0	10	52	31
AA	0.06	0.126	0.040	0.037	0.052	210.0	67	62	87
AP-2	0.01	0.360	0.079	0.163	0.113	3600.0	790	1630	1130
AP-2	0.11	0.238	0.051	0.004	0.021	210.0	46	4	19
AP-2	0.15	0.182	0.076	0.071	0.089	120.0	50	47	59
AS	4.30	0.941	0.770	2.780	2.070	22.0	18	65	48
AS-4	0.16	0.359	0.014	0.214	0.018	220.0	9	134	11
AS-4	0.01	0.075	0.129	0.251	0.201	750.0	1290	2510	2010
AS-4	0.12	0.074	0.053	0.059	0.026	61.0	44	49	22
BJ	0.92	0.553	0.677	0.616	0.593	60.0	74	67	64
BK	0.27	0.130	0.012	0.022	0.145	48.0	5	8	54
BS	0.03	0.371	0.106	0.227	0.512	1200.0	350	750	1700
BS	0.14	0.186	0.047	0.047	0.011	130.0	33	33	8
BS	0.16	0.130	0.043	0.034	0.056	81.0	27	21	35
BU, BW, BX	0.21	0.014	0.253	0.008	0.203	7.0	120	4	97

shows that the predicted value was either 0.06 or 0.02 acres whereas the actual value was 0.04 acres. Without question Table 6 shows that the percentage values of deviations for the logarithmic model (Equations 9, 10 and 11) are less than for the linear model. It is significant that 28 out of 61 values exceed 100 percent for the linear model, but only 12 exceed 100 percent for the logarithmic models. A further analysis of the 12 samples that exceed 100 percent in the latter model shows that eight of these samples were common to all three equations and occurred where the Y value was 0.07 acres or less. The equations thus erred considerably in the direction of over-predicting the above 12 values. Therefore it was concluded from the data in this study that the gullying process is best represented by the functional relationship in Equation 10.

Regression analysis for change in gully length

An analysis of the change in gully length for the three periods was made with the use of the same data that were used in the surface area analysis. Prediction equations were derived from a logarithmic model. An equation which satisfactorily represented the data was not obtained. The R^2 values for Equations 11, 12 and 13 are 0.10, 0.20 and 0.24 respectively. Thus it is evident that extreme variation remains after fitting the logarithmic model. Table 7 includes the derived equations. They are listed to illustrate the apparent inconsistencies in the signs of the selected variables relative to signs arrived at by intuitive reasoning. The equations are not recommended for use as equations which express the process of gully elongation.

Table 7. Regression equations to predict change in gully length using a logarithmic model^a

No.	Equations
11	$X_{12} = 2.63 X_4^{0.0169} X_8^{0.2127} X_{14}^{0.332} e^{-0.0206X_3}$
12	$X_{12} = 0.036 X_4^{-0.429} X_5^{1.732} X_8^{0.0892} X_{14}^{0.624} e^{-0.0634X_3}$
13	$X_{12} = 0.001 X_2^{-0.3637} X_4^{-0.3709} X_5^{\underline{1.71}} X_6^{-0.0172} X_7^{\underline{-1.5119}} X_8^{1.479} e^{\underline{-0.0596X_3}}$

Where: X_2 = Watershed area (Ac)
 X_3 = Deviation of precipitation from normal (In)
 X_4 = Index of surface runoff (In)
 X_5 = Length of period (Yr)
 X_6 = Terraced area of watershed (Ac)
 X_7 = Ratio of gully length, L_1 , at beginning of period to total length, L , from outlet to watershed divide
 X_8 = Gully length, L_1 , at beginning of period (Ft)
 X_{12} = Change in gully length (Ft)
 X_{14} = Length from end of gully to watershed divide (Ft)
 e = 2.71828 (Base of natural logarithm)

^aThe underlined coefficients in this table indicate a significance level of 95 percent or greater.

SUMMARY AND CONCLUSIONS

The major objective of this study was to define a functional relationship which describes the gully development phenomena in western Iowa. A relationship for this phenomena would permit more accurate predictions of future rates of gully development. Since no controlled studies of individual components responsible for the gullying process have been made, a study of this subject must of necessity involve a historical approach where all variables are evaluated on the basis of the past growth of gullies.

Steer Creek Watershed, a gullied area in Harrison County, Iowa, was used for this gully study. The rates of gullying were determined with the use of controlled aerial flights, supplemented with a topographic survey which was made on the watershed 20 years ago. The hydrologic and watershed factors which were postulated to effect gullying were evaluated for the same period as for the gully growth. With the data available it was possible to divide the analysis into the following four parts:

1. Growth of the main and lateral gullies prior to 1938.
2. Growth of the main after 1932.
3. Geometric relationships within the gully cross section and profile.
4. Development of prediction equations for gully growth by use of multiple regression techniques.

The history of the development of the main and lateral gullies in Steer Creek is very interesting. The earliest records available show

that in 1852 there were five narrow laterals ranging from 2 to 5 feet in width. Today there are more than 25 lateral gullies. Based on interviews and existing landmarks, it has been possible to show that the major portion of the development of the main gully has occurred since 1932. With the exception of two laterals, the lateral gully development has occurred since 1915.

The major emphasis in this study was directed to the evaluation of the lateral gully development since 1938. The gully, hydrologic and watershed data were programed for the IBM 650 computer. From the programed data prediction equations based on two models were obtained for the change in gully surface area and change in gully length. These models were the characteristic linear model and a logarithmic model which multiplies the independent factors in the prediction equation. Although different hydrologic, gully and watershed variables and combinations of these variables were used, the prediction equation for change in gully surface area which most nearly represents the gully development phenomena is

$$X_1 = 0.01 X_4^{0.0982} X_6^{-0.0440} X_8^{0.7954} X_{14}^{-0.2473} e^{-0.0360X_3} \quad (10)$$

Where: X_1 = Change in gully surface area in acres.

X_3 = Deviation of precipitation from normal in inches.

X_4 = Index of surface runoff in inches.

X_6 = Terraced area of watershed in acres.

X_8 = Gully length, L_1 , at beginning of period in feet.

X_{14} = Length from end of gully to watershed divide in feet.

The conclusion that the functional relationship for the gullying process is a logarithmic relationship is supported by the fact that the deviations from the fitted curve are smaller for the logarithmic model (Equations 9, 10 and 11) than for the linear model (Equation 8).

Equation 10 was selected as the most desirable prediction equation. It represents the logarithmic relationship, and the coefficients also have correct signs according to intuitive reasoning.

Use of Regression Equation

One of the objectives of this study was to provide guidance in the prediction of rates of gully growth. The validity of Equation 10 as a prediction equation for the population of gullies in the loess soil region can be verified only when additional data are obtained on other gullies. In order to use Equation 10 to predict future gully development, a decision would have to be made on how to evaluate the hydrologic variables of runoff and precipitation for a period in the future. In this study, these variables were evaluated from past weather records. Therefore hydrologic data pertaining to a future period also would have to be based on previous weather records. The hydrologic and land management factors cannot be assumed to be independent of one another. The time of occurrence of a given hydrologic and land management sequence will have to be assumed. Since periods of 4 to 20 years were used as intervals for evaluating the data in this study, it is recommended that the period of time be limited to 10 years when using Equation 10 as a

prediction equation.

Need for Research

This gully study has determined the general functional relationship for the gully development process. It will serve as a guide for the direction of future gully research. The problems involved in a study of this nature are numerous. The most difficult problem is to determine and accurately compute the value of the pertinent variables for a past period of gully development. This problem would be minimized by controlled gully studies and points out the necessity of initiating such a study, particularly since several years data are required before an analysis can be made.

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APPENDIX: HYDROLOGIC, GULLY GROWTH AND WATERSHED DATA
FOR GULLIES IN STEER CREEK WATERSHED

Table 8. Hydrologic, gully growth and watershed data for gullies in Steer Creek Watershed

Lateral	Period	Gully area (Ac)		Water-shed area (Ac)	Precipitation deviation (In)	Index of runoff (In)	Gully length (Ft)		Water-shed length (Ft)	Area terraced (Ac)
		Beginning	Ending				Beginning	Ending		
0	1938-49	4.36	7.46	231.2	-2.60	3.49	2175	2900	3050	0
0-14	1938-49	0.46	0.74	56.3	-2.60	3.49	300	350	2850	0
0-15	1938-49	1.32	3.56	65.3	-2.60	3.49	1450	2175	2320	0
U	1938-42	0.00	0.04	67.2	-9.19	3.15	0	100	3940	0
U	1942-49	0.04	0.11	67.2	+6.59	9.22	100	250	3940	0
U	1949-61	0.11	0.14	67.2	+13.87	27.56	250	360	3940	0
U-2	1938-42	0.00	0.11	13.2	-9.19	2.76	0	213	1640	0
U-3	1942-61	0.12	0.28	6.7	+20.46	28.28	150	260	1380	0
W-3	1938-42	0.00	0.14	10.1	-9.19	3.76	0	240	2000	0
W	1938-49	0.17	0.29	114.7	-2.60	18.29	250	350	3900	0
Z-1	1938-49	0.11	0.29	5.5	-2.60	15.22	250	400	1150	0
Z	1938-49	2.18	6.25	106.8	-2.60	15.90	3000	3150	5150	0
AB-6	1938-61	1.20	2.20	37.8	+11.27	32.11	925	1240	2360	0
AB-16	1938-49	2.60	4.20	62.0	-2.60	16.81	1000	1575	2940	0
AB-16	1949-61	4.20	5.70	62.0	+13.87	24.88	1575	1840	2940	0

Table 8. (Continued)

Lateral	Period	Gully area (Ac)		Water-shed area (Ac)	Precipitation deviation (In)	Index of runoff (In)	Gully length (Ft)		Water-shed length (Ft)	Area terraced (Ac)
		Beginning	Ending				Beginning	Ending		
AB-20	1938-49	0.30	0.90	17.7	-2.60	17.38	350	600	1420	0
AB-20	1949-61	0.90	1.50	17.7	+13.87	24.88	600	840	1420	0
AB-22	1938-49	1.00	1.60	14.7	-2.60	14.42	625	750	1340	0
AB	1938-49	28.60	38.00	364.5	-2.60	16.01	7000	7200	8000	0
AX-9	1942-61	0.18	0.47	27.2	+20.46	46.00	193	320	1600	0
AX-10	1938-49	0.17	0.53	25.9	-2.60	18.29	250	600	1700	3.26
AX 81+35	1938-49	0.15	0.56	20.3	-2.60	18.29	200	450	1780	1.47
AX 0+00	1938-42	4.07	6.54	610.0	-9.19	4.50	1700	2018	9920	0
AX 0+00	1942-49	6.54	7.05	610.0	+6.59	11.86	2018	2850	9920	0
AX 0+00	1949-61	7.05	7.50	610.0	+13.87	28.00	2850	3480	9920	0
AZ 0+00	1938-49	0.92	1.78	145.3	-2.60	14.08	750	1000	6350	0
AZ 0+00	1949-61	1.78	1.85	145.3	+13.87	26.81	1000	1240	6350	10.50
AZ 0+00	1942-61	1.37	1.85	145.3	+20.46	37.47	890	1240	6350	10.50
BL	1942-61	0.14	0.22	20.8	+20.46	37.91	190	300	2340	0.33
CA	1938-42	0.05	0.17	49.7	-9.19	2.57	100	400	3000	0

Table 8. (Continued)

Lateral	Period	Gully area (Ac)		Water-shed area (Ac)	Precipitation deviation (In)	Index of runoff (In)	Gully length (Ft)		Water-shed length (Ft)	Area terraced (Ac)
		Beginning	Ending				Beginning	Ending		
CA	1942-49	0.17	0.40	49.7	+6.59	8.09	400	450	3000	0
CD	1942-49	0.48	0.75	54.6	+6.59	10.35	550	700	3420	0
CH	1938-42	0.06	0.14	22.2	-9.19	3.53	150	264	2400	0
CH	1942-49	0.14	0.19	22.2	+6.59	9.98	264	275	2400	0
CK	1942-49	0.27	0.45	85.0	+6.59	11.48	427	500	4050	0
CO	1938-42	0.66	0.88	130.2	-9.19	4.65	575	712	4800	0
CO	1942-49	0.88	1.15	130.2	+6.59	12.16	712	750	4800	0
CX	1938-42	2.70	3.90	686.0	-9.19	3.96	1300	1610	10800	0
AA-1	1938-42	1.50	3.04	109.0	-9.19	2.72	1700	2000	4200	0
AA-1	1942-61	3.04	3.54	109.0	+20.46	10.38	2000	2100	4200	2.9
AA-1a	1942-61	0.05	0.47	37.0	+20.46	10.38	150	950	2040	0
AA-2	1942-61	0.22	0.26	32.8	+20.46	10.38	250	270	2510	0
AA-5	1942-61	0.27	0.40	22.3	+20.46	32.31	360	420	2120	0
AA-5	1938-49	0.25	0.34	22.3	-2.60	11.01	275	400	2120	0
AA-10	1942-61	0.39	0.89	52.5	+20.46	44.41	440	440	2060	0

Table 8. (Continued)

Lateral	Period	Gully area (Ac)		Water-shed area (Ac)	Precipitation deviation (In)	Index of runoff (In)	Gully length (Ft)		Water-shed length (Ft)	Area ter-raced (Ac)
		Beginning	Ending				Beginning	Ending		
AA-12	1942-61	0.56	0.59	37.0	+20.46	44.19	410	410	1540	3.76
AA Main	1938-42	0.23	0.46	37.1	-9.19	4.50	300	318	2020	0
AA Main	1942-61	0.46	0.52	37.1	+20.46	46.65	318	420	2020	8.20
AP-2	1938-42	0.05	0.06	13.4	-9.19	4.65	100	110	990	0
AP-2	1942-49	0.06	0.17	13.4	+6.59	10.20	110	200	990	0
AP-2	1942-61	0.06	0.21	13.4	+20.46	37.91	110	230	990	0
AS Total	1938-49	8.90	13.20	422.0	-2.60	13.29	2775	2900	6230	0
AS-4	1938-42	0.11	0.27	45.3	-9.19	4.42	350	400	2480	0
AS-4	1942-49	0.27	0.28	45.3	+6.59	11.71	400	440	2480	0
AS-4	1942-61	0.27	0.39	45.3	+20.46	41.72	400	660	2480	0
BJ	1938-42	0.29	1.21	64.4	-9.19	3.99	300	400	3170	0
BK	1938-42	0.40	0.67	56.2	-9.19	4.34	260	360	2480	0
BS	1938-42	0.11	0.14	19.6	-9.19	4.57	200	240	1820	0
BS	1942-49	0.14	0.28	19.6	+6.59	12.01	240	250	1820	0
BS	1942-61	0.14	0.30	19.6	+20.46	36.12	240	340	1820	0
BU,BW,BX	1942-61	1.59	1.80	148.0	+20.46	39.03	520	660	3420	0